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Translated from Russian

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# THE ASTROPHYSICS OF COSMIC RAYS

(Kosmicheskie luchi u zemli i vo vselennoi)

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## INTRODUCTION

It was established about fifty years ago that some kind of "radiation" is constantly arriving at the earth from outer space. This radiation, known as cosmic radiation, is highly penetrating and can even pass through thick layers of lead.

The discovery of cosmic rays came as a result of studies of the dark current in ionization chambers. As early as the beginning of the present century, it was found that a current (the so-called dark current) exists in an ionization chamber even in the absence of any artificial sources of ionization. The presence of this current in ionization chambers located near the earth's surface could have been due to radioactive impurities in objects in the vicinity of the chamber. Therefore, the extraterrestrial origin of a certain part of the dark current was demonstrated only after balloon experiments were carried out. The current generated in an ionization chamber by the radioactivity of the earth or various terrestrial objects would have to decrease in proportion to the distance of the chamber from the earth's surface. However, as it turned out, the ionization current diminished with height only up to low altitudes, after which it began to increase. For example, in experiments carried out in 1914, when a height of 9 km was attainable, the ionization at this altitude was found to be about ten times that at sea level. It is true that even after these experiments cosmic rays were still thought by some to have a terrestrial origin; for instance, they were associated with thunderstorms and with the radioactivity of the upper layers of the atmosphere. However, all these hypotheses finally had to be abandoned.

Because of the great penetrating power of cosmic rays, they were at first thought to be a variety of $\gamma$-radiation. Later it was ascertained that the primary cosmic radiation includes charged particles. This was established using the magnetic field of the earth, since a charged particle moving in this field becomes deflected. Thus, the flux of primary cosmic rays (that is, the rays entering the earth's atmosphere) depends on the geomagnetic latitude of the observation point. In the atmosphere the primary cosmic rays produce secondary particles, and only the latter are observed at the earth. The dependence of the secondary flux on the geomagnetic latitude, however, indicates that charged particles are present in the primary flux. For a long time the direct investigation of the primary cosmic rays was almost impossible, due to the difficulty of getting measuring equipment up to high altitudes. The lack of reliable data on primary cosmic rays thus precluded a determination of their origin, so that the origin of cosmic rays remained an open question for many years.

The situation did not change substantially even after it was demonstrated that primary cosmic rays consist mostly of protons and the nuclei of various elements (the presence of nuclei was established in 1948). The point is that cosmic rays have an isotropic distribution, that is, they arrive at the earth uniformly from every direction. Consequently, a study of these rays does not afford any direct information concerning the place where the radiation sources are located. In order to see better how the isotropy of cosmic radiation hinders a solution of the problem of its origin, let us imagine that the optical radiation of all the celestial bodies is blended together and then an attempt is made to analyze it. In such a case, instead of studying the spectrum and intensity of the luminous emission of individual stars and nebulae, it would be necessary to consider the characteristics of the radiation from all such objects, together with the ones in question. Clearly, under such conditions almost nothing would remain of what we know as astrophysics. Analogously, the information on primary cosmic rays pertains equally to all the radiation sources.

Is it possible in general to obtain information on the cosmic rays in various regions of the universe far away from the earth? Quite recently it would still have been necessary to answer this question in the negative. However, as has more than once been the case in the history of physics and astronomy, the situation has undergone a rapid and radical change as a result of certain discoveries made in a completely different field. The field referred to is radio astronomy, which began to be developed intensively after 1945. Between the years 1950 and 1953 it was established that most of the radio emission arriving at the earth from space is generated by cosmic rays (more precisely, by the electron component of cosmic rays). An analysis of the cosmic radio emission gave us an indication of certain characteristics of cosmic rays not only in our own stellar system, the Galaxy, but also far beyond its limits as well. The development of radio astronomy, together with the recognition of the relation between cosmic radio emission and cosmic rays, have led to the following result: the question of the origin of cosmic rays and the determination of their properties in different regions of the universe are now important topics in astrophysics. In this respect it has been possible, just as in the solution of other astrophysical problems, to take the observational data as a basis and to carry out an analysis using all the various information obtained by different methods. Cosmic rays are of interest not only as an independent object of study. In addition they have been found to play a substantial role in the dynamics of the interstellar medium and supernova shells, as well as being one of the main factors determining the evolution of galaxies.

The radio-astronomical method of studying cosmic rays far away from the earth is the most important method, but it is not the only one possible. Recently it was found that definite, and in some cases extremely valuable, information on cosmic rays can also be obtained using the new sciences of gamma-ray and x-ray astronomy. Moreover, even classical optical astronomy provides cosmic-ray information for a number of astronomical objects.

The techniques and the results of some studies of primary cosmic rays will be described below. First, however, let us make two additional remarks concerning the present stage in the development of the astrophysics and physics of cosmic rays.

The appearance of a number of new methods (such as radio astronomy, gamma-ray and x-ray astronomy, the study of primary cosmic rays near the earth, neutrino astronomy, and some others) did not just represent an important step forward in the development of astronomy; rather, it led to an actual revolution in astronomical research. As recently as twenty years ago, earth-based optical telescopes still had a monopoly on astronomical observations. Such telescopes can pick up cosmic electromagnetic radiation lying just in the approximate range from 0.3 micron to several microns. Now, on the other hand, it is possible to pick up (and this is actually already being done) waves with lengths ranging from hundreds of meters and even kilometers down to billionths of a micron. This fact, together with the possibility of recording cosmic rays and neutrinos and the possibility of studying interplanetary space directly using rockets, has widened to a colossal degree those channels via which information concerning the Universe comes to us. In this small book, however, we will only be able to discuss astronomical problems directly related to cosmic rays. *

Studies of the primary cosmic rays near the earth (the measurements being made using balloons, rockets, and satellites) have traditionally been a part of cosmic-ray physics rather than astronomy. The field of cosmic-ray physics has almost always been distinguished by two main trends. The first of these is the use of cosmic rays to study elementary particles and their interactions at high energies. This actually involves a utilization of favorable opportunities for observing high-energy particles. These opportunities have been utilized very successfully; positrons, $\mu^{\pm}$, $\pi^{\pm}$, and K mesons, and also some hyperons, were all discovered in cosmic rays. The study of such particles is so important that, for a long time (especially from 1929 to about 1955 or 1956), elementary-particle research was the main aspect of cosmic-ray physics. However, the situation changed considerably when powerful accelerators were developed. In the energy range attainable with accelerators (up to $3 \cdot 10^{10}$ ev), cosmic rays are not in general a better means of studying elementary particles. Consequently, the emphasis of the first trend in cosmic-ray physics (usually called the nuclear-physical trend) has been shifted into the range of energies above $3 \cdot 10^{10}$ ev. The maximum energy which has been recorded in cosmic rays is about $10^{20}$ ev. Thus it is quite obvious that cosmic rays will probably continue to be a useful tool for purely physical research for a very long time to come. **

Nevertheless, the relative importance of elementary-particle research in cosmic-ray physics has undoubtedly diminished considerably. Thus, in recent years, the second trend in cosmic-ray physics (namely the study of

* Some results and developmental tendencies in astrophysics are discussed in a paper by the author: Sovremennaya astrofizika (Modern Astrophysics). — In Sbornik: Nad chem dumayut fiziki, No. 6, Astrofizika, Izdatel'stvo Nauka. 1967.

** Energies which are about one billionth of the maximum energies of cosmic-ray particles are now attainable with accelerators. In the next few years it will hardly be possible to build accelerators producing particles with energies greater than $3 \cdot 10^{11}$ ev. It is true that using the so-called crossing-beam method (which however involves certain major difficulties) it is actually possible to study the collisions of particles with energies $E'=2(E/Mc^2)^2Mc^2$, where $E$ is the energy of the particles in each of the beams, the rest mass of the particles being $M$. However, for electrons, even when $E = 5 \cdot 10^9$ ev, the energy $E' = 10^{14}$ ev, for protons, when $E = 3 \cdot 10^{10}$ ev, the energy $E' = 2 \cdot 10^{12}$ ev.

The use of cosmic rays to study the structure of matter has been discussed in the following popular books: DOBROTIN, N.A. Kosmicheskie luchi (Cosmic Rays). — Izdatel'stvo AN SSSR. 1963; ZHDANOV, G.B. Chastitsy vysokikh energii (High-Energy Particles). — Izdatel'stvo Nauka. 1965; and ROSSI, B. Cosmic Rays. — McGraw-Hill. 1964.

the geophysical and astrophysical aspects of cosmic rays) has begun to become the major one. At present the number of works on the geophysical and astrophysical aspects of cosmic rays has risen to considerably more than half of all the studies devoted to cosmic rays. The subjects of these works are:

primary cosmic rays near the earth (chemical composition, energy spectrum, lateral distribution); here only cosmie rays of nonsolar origin are referred to;

solar cosmic rays, their generation, earthward motion, and effect on the earth's ionosphere;

the effect which the interplanetary medium and the interplanetary magnetic fields have on cosmic rays (of both solar and galactic provenance): high-latitude cutoff and various changes in cosmic rays both near the earth and throughout the solar system;

the radiation belts near the earth and other planets.

Launchings of artificial satellites and space probes, together with the general progress in geophysics and solar physics, have led to the appearance of a large number of works on all the above subjects. These various studies are all interrelated, and in addition they are related to other scientific fields as well (solar physics, the physics of interstellar and interplanetary space, particle-acceleration theory, radio astronomy, etc.).

The field of research which may be called the astrophysics of cosmic rays includes all the information which has been gathered on cosmic rays near the earth and in the universe as a whole, together with any other relevant astronomical and physical data and all relevant theoretical considerations. The purpose of this book will be to describe the present state of this field of study. *

* More detailed descriptions of the astrophysics of cosmic rays will be found in the monograph: GINZBURG, V. L. and S. I. SYROVATSKII. Proiskhozhdenie kosmicheskie luchi (The Origin of Cosmic Rays). — Izdatel'stvo AN SSSR. 1963, and in the following papers by the same authors, published in the journal Uspekhi Fizicheskikh Nauk: Vol. 84, p. 201. 1964; Vol. 87, p. 65. 1965; Vol. 88, p. 485. 1966.

*Chapter 1*

# *PRIMARY COSMIC RAYS NEAR THE EARTH*

A column of the earth's atmosphere 1 $cm^2$ in area has a mass of about 1 kg. From the point of view of the penetration through it of various types of radiation, such an air filter is equivalent to a water layer 10 meters in thickness. The mean free paths of the particles making up primary cosmic rays are less than 1 meter of water (that is, less than 100 $g/cm^2$). Consequently, the atmosphere serves as a thick filter for primary cosmic rays, and it is practically impossible for these rays to reach the earth's surface. Even up on high mountains the situation is essentially the same, and the primary particles constitute only a small fraction of the total cosmic-ray flux. Thus, primary cosmic rays (and only the primaries will be of interest to us here) can be studied solely by means of sounding balloons, high-altitude aircraft, rockets, and artificial satellites. So far, sounding balloons have been the main tool used for such research, but an ever-increasing use of satellites and rockets in the future is to be expected.

The photoemulsion method is usually used to determine the chemical composition of the primaries, but Čerenkov counters can also be employed. It is important to note that the nuclei in cosmic rays are "bare" nuclei, which have no orbital electrons. In this case both the ionization strength and the Čerenkov-radiation intensity, other conditions being equal, are proportional to $Z^2$, where Z is the atomic number of the nucleus. Nuclei with different Z will have different tracks in an emulsion (Figure 1). In a Čerenkov counter (Figure 2), different nuclei can be distinguished according to the intensity of the burst of Čerenkov radiation.

The energy spectrum of the cosmic radiation (number of particles as function of particle energy) is determined according to the lateral distribution of the cosmic-ray flux. The use of this method is limited to energies below about 15 Bev for protons and below about 7.5 Bev/nucleon for nuclei.*

* Let us explain briefly why there is such a difference between the energy limits for protons and nuclei. The frequency of revolution of a particle with a charge $eZ$, a total energy $E$, and a mass $M$, moving in a magnetic field of intensity $H$, is $\omega_H^* = \frac{eZH}{Mc}\frac{Mc^2}{E}$. The radius of curvature of the corresponding particle trajectory if the particle velocity $v$ is normal to the field $H$, is $r = v/\omega_H^* = R_H/H$. The quantity $R_H = \frac{pc}{eZ} = \frac{vE}{eZc}$ is called the magnetic rigidity ($p = vE/c^2$ is the particle momentum). For ultrarelativistic particles $v/c \approx 1$ (that is, $p \gg Mc$, $\frac{E}{Mc^2} = \left(1 - \frac{v^2}{c^2}\right)^{-1/2} \gg 1$) and the radius $r = E/eZH$. In

FIGURE 1. Tracks of relativistic nuclei with different $Z$ in photo-emulsion. As seen, higher $Z$ corresponds to a heavier track.

the latter case, if $r$ is measured in cm, $E$ in ev, and $H$ in oersteds,

$$r=\frac{E}{300ZH}=\frac{A\varepsilon}{300ZH}, \tag{1}$$

where $E=A\varepsilon$, $A$ being the atomic weight and $\varepsilon$ being the total energy per nucleon.

The probability of a particle reaching the earth is obviously determined by the radius of curvature of its trajectory in the earth's magnetic field. For protons $A/Z=1$, and for nuclei $A/Z\approx2$ (the nuclei of tritium and $He_2^3$ constitute exceptions). Therefore, the earth's magnetic field, which prevents protons with $E<15$ Bev from reaching the equator (in a vertical direction), does not keep cosmic-ray nuclei with energies $\varepsilon>7.5$ Bev/nucleon from reaching the equator.

At higher energies the energy spectrum may be determined according to the number of particles with some given energy, as recorded on emulsions. This method provides a certain amount of information up to energies of around $10^{12}$ to $10^{13}$ ev ($10^3$ to $10^4$ Bev). For energies even higher than these, cosmic rays are studied almost exclusively in extensive air showers (this will be discussed below).

FIGURE 2. Čerenkov counter: a) transparent plastic detector; b) photomultiplier.

A fast charged particle penetrating the detector emits light (Vavilov–Čerenkov effect), which is recorded via the photomultiplier.

Studies of primary cosmic rays consist in determining their composition (the number of particles with different charges and masses), the energy spectrum of particles of different types, and the lateral (or, more precisely, angular) distribution. No complete solutions have as yet been found for any of these problems, but studies are being carried out by many groups in various countries and progress is certain to be rapid. Some basic results which are believed to be more reliable will be given below.

## CHEMICAL COMPOSITION

Unfortunately, the charge on each given nucleus (as observed, for example, in a photographic emulsion) can only be determined very approximately. Moreover, when the measurements are made using balloons, there is still a layer of air several g/cm$^2$ thick above the equipment. For instance, in one of the measurements with the most favorable conditions, this layer was 2.7 g/cm$^2$ (the height of ascent was a little over 40 km). Usually, though, such measurements are made at lower altitudes (layer thickness from 5 to 10 g/cm$^2$). Nuclei are already being studied using satellites, but the determination of the chemical composition of cosmic rays from satellite measurements is also associated with certain difficulties (use of a photographic method requires "recovery" of the photographic plates, while if Čerenkov counters are employed quite thick detectors are necessary). When there is a layer of matter over the measuring equipment, some of the nuclei recorded using an emulsion (or any other method) will be secondary; these are produced, for example, in the air above the equipment. Finally, in order to obtain accurate enough values of $Z$, the tracks of a large number of nuclei under the very same conditions must be studied. This is especially difficult for rarely encountered elements. In view of the foregoing, it is easy to see why the existing data on the chemical composition of primary cosmic rays are still far from complete. To raise the statistical accuracy, data are usually obtained for groups of nuclei, rather than for individual particles. For example, the nuclei of lithium, beryllium, and boron ($Z$ from 3 through 5) make up the group of light nuclei ($L$ group). The nuclei of carbon, oxygen, nitrogen, and fluorine ($Z$ from 6 through 9) form the group of medium nuclei ($M$ group). Lastly, all nuclei with $Z \geqslant 10$ are classified as heavy nuclei ($H$ group). Sometimes nuclei with $Z \geqslant 20$ are classified separately as very heavy nuclei ($VH$ subgroup). Protons ($p$ group) and helium nuclei, or $\alpha$-particles ($\alpha$ group), are considered separately from the other nuclei.

Except for a small number of slow particles, existing methods do not enable us to determine the atomic weights of cosmic-ray nuclei. In other words, all the isotopes of a given element are measured together. Therefore, strictly speaking, the $p$ group includes protons, deuterons, and tritium nuclei, while the $\alpha$ group includes $He_2^3$ nuclei as well as $He_2^4$ nuclei. The flux $I$ is determined for each of these groups, that is, the number of particles incident upon a unit area per unit time per unit solid angle (per steradian). In the following, $I$ will be measured in particles/$m^2$ ster sec. It would be more accurate to call the quantity $I$ the intensity or the flux in a given direction, but the term "flux" is more widely used. The total flux $F$ is obtained by integrating over the angles. For isotropic radiation, with integration over a hemisphere,

$$F = \int I \cos\theta \, d\Omega = \pi I.$$

The fluxes for the above-mentioned nuclei groups are listed in Table 1. The mean atomic weight $\bar{A}$ for each group (3rd column of table) is determined from the same experimental data used to find the fluxes. In all cases the values given for $I$ pertain to particles with total energies greater than 2.5 Bev/nucleon. $\bar{A}I$ indicates the number of nucleons in the cosmic-ray flux.

The sixth column of Table 1 shows the ratio of the flux of nuclei in a given group to the flux of nuclei in group $H$; this ratio is also equal to the ratio $N/N_H$ of the concentrations of nuclei in the corresponding groups. Here it is taken into account that, for an isotropic angular distribution of particles, the concentration $N = 4\pi I/v$, where $v$ is the particle velocity. For the relativistic particles in question, it is accurate enough to set $v = c = 3 \cdot 10^{10}$ cm/sec. The last two columns of the table show the ratios $N/N_H$ (obtained according to different data), characterizing the average abundances of the elements in the universe (sun, stars, and interstellar space).

As the table shows, the chemical composition of cosmic rays has two important characteristics. First, only a very small amount of the light elements (lithium, beryllium, and boron) exists in nature. These elements "burn up" rapidly in the stars. In cosmic rays, however, the elements of group $L$ are about as abundant as the heavy elements (group $H$), that is, about $10^5$ times more abundant than the average for nature.

TABLE 1. Chemical composition of cosmic rays*

| Nuclear group | $Z$ | $\overline{A}$ | $I$ | $\overline{A}I$ | $\frac{I}{I_H}=\frac{N}{N_H}$ | In universe (average) $\frac{N}{N_H}$ | |
|---|---|---|---|---|---|---|---|
| $p$ | 1 | 1 | 1300 | 1300 | 650 | 3360 | 6830 |
| $\alpha$ | 2 | 4 | 94 | 376 | 47 | 258 | 1040 |
| $L$ | 3–5 | 10 | 2.0 | 20 | 1.0 | $10^{-5}$ | $10^{-5}$ |
| $M$ | 6–9 | 14 | 6.7 | 94 | 3.3 | 2.64 | 10.1 |
| $H$ | $\geqslant 10$ | 31 | 2.0 | 62 | 1.0 | 1 | 1 |
| $VH$ | $\geqslant 20$ | 51 | 0.5 | 25 | 0.26 | 0.06 | 0.05 |

* The chemical composition of the interstellar gas as a whole is given by the numbers in the last two columns, which correspond to different sets of existing data.

Second, cosmic rays are considerably richer in heavy and very heavy elements, in comparison with the celestial bodies. Actually, in cosmic rays there are approximately 700 protons and $\alpha$-particles for every nucleus of group $H$ and about 2000 protons and $\alpha$-particles for every nucleus of group $VH$ (the latter being mostly iron and chromium nuclei). On the other hand, the average in the universe, according to different data, is 3600 to 8000 protons and $\alpha$-particles per nucleus of group $H$ and 60, 000 to 160, 000 protons and $\alpha$-particles per nucleus of group $VH$. This means that, even if we take the lower values of 3600 and 60,000, cosmic rays have five times as many heavy elements and thirty times as many very heavy elements as the sun, the stars, and the interstellar gas.

The presence of lithium, beryllium, and boron in cosmic rays can be explained as follows. As cosmic rays move through interstellar space, the nuclei of groups $M$ and $H$ become divided as a result of nuclear collisions with the nuclei of atoms of the interstellar medium (mainly protons and helium nuclei). Some of the products of these disintegrations are nuclei of group $L$, which are therefore secondary. The very low abundances of these nuclei in nature would lead us to assume that the same is true in the cosmic-ray sources. Taking into account the relatively large number of $L$ nuclei in the cosmic rays near the earth, and assuming that all these nuclei are secondary, we may conclude that the cosmic rays come from far away. On the average, they should have passed through a layer of matter from 2 to 10 g/cm$^2$ thick. The average concentration of gas in our Galaxy is about 0.01 particles per cm$^3$, corresponding to a density of $2 \cdot 10^{-26}$ g/cm$^3$ (for more details, see below). Thus the cosmic rays reaching the earth have, on the average, traversed a distance of the order of $3 \cdot 10^{26}$ cm. A particle moving at nearly the velocity of light will cover this distance in a time $T_{\text{c.r.}}$ of the order of $10^{16}$ sec $\approx 3 \cdot 10^{8}$ years.

Only measurements of the number of all $L$ nuclei taken together were referred to above. This number is determined by the thickness of intergalactic gas traversed by the cosmic rays, a quantity which can be evaluated from the above measurements (the previously mentioned uncertainty of this thickness, from 2 to $10\,g/cm^2$, is explained by the inaccuracy of existing data on the probability that different nuclei will disintegrate to produce Li, Be, and B atoms). It is interesting that a determination of the relative composition of the group of $L$ nuclei provides a direct evaluation of the travel time $T_{c.r.}$ of cosmic rays through interstellar space,* as well as giving us more precise information on the thickness of the gas layer through which the rays have passed. This is because one of the isotopes of beryllium is the radioactive isotope $Be_4^{10}$, which, with a half-life of $3 \cdot 10^6$ years, changes into a $B_5^{10}$ nucleus. If the cosmic-ray "lifetime" $T_{c.r.} \gg 3 \cdot 10^6$ years, then there will be more B nuclei in the cosmic rays than for $T_{c.r.} \lesssim 3 \cdot 10^6$ years (in the latter case most of the $Be_4^{10}$ nuclei would not have had time to change into $B_5^{10}$ nuclei). Preliminary data obtained in this way indicate that $T_{c.r.} \gtrsim 5 \cdot 10^7$ years, which does not contradict the value $T_{c.r.} \sim 3 \cdot 10^8$ years given above.

Our Galaxy has a radius of about $R = 3 \cdot 10^{22}$ to $5 \cdot 10^{22}$ cm $\approx$ 30,000 to 50,000 light years. The distance traversed by cosmic rays ($3 \cdot 10^{26}$ cm) is considerably greater than the radius of the Galaxy. Thus one might conclude that cosmic rays come from regions located far beyond the limits of the Galaxy. However, such a conclusion would be somewhat premature, since there are magnetic fields in interstellar space which have intensities $H \sim 10^{-6}$ to $10^{-5}$ oersted. The curvature radius of the trajectory of a proton with an energy $E = 10^{10}$ ev = 10 Bev (a typical value for cosmic rays) is $r = E/300H \approx 3 \cdot 10^{13}$ cm, even in a very weak field of $10^{-6}$ oersted, that is, it is negligibly small in comparison with galactic dimensions. The configurations of the interstellar magnetic fields determine the nature of the motion in the Galaxy of cosmic rays with a low enough radius of curvature. A charged particle in a uniform magnetic field moves along a helix, and its velocity along the field equals the component $v_\parallel$ of the total velocity $v$ along the field. Therefore it may be assumed that, as an average over a quite long period, a particle moves rectilinearly through a uniform field with a velocity $v_\parallel$. However, if the force lines of the field are bent so that they form a random "bell," the particle will move along a complex trajectory; as a first approximation, this trajectory can be assumed to lie along a line of force. If the motion is in an "entangled" magnetic field with a complex configuration, the movement of the particle in any direction may be compared to molecular diffusion in a gas. A diffusing molecule describes a complex trajectory, consisting of rectilinear segments each equal in length to the mean free path (the distance between collisions of a given molecule with the atoms or molecules of the gas). For motion in an irregular magnetic field, the role of the mean free path is played by the characteristic distance $l$ over which the direction of the force lines varies substantially (Figure 3). Finally, the analogy between diffusion in a gas and motion in a magnetic field is a restricted one, and it will be of sufficient accuracy only when a whole set of conditions are satisfied. It may be assumed that in galactic magnetic fields these conditions are satisfied to

* Before, we evaluated $T_{c.r.}$ at about $3 \cdot 10^8$ years by dividing the path traversed ($3 \cdot 10^{26}$ cm) by the velocity of light ($c = 3 \cdot 10^{10}$ cm/sec). Then, however, it was assumed that, even at the source, a cosmic ray does not move through regions where the gas density is substantially higher than the average. Thus it is of independent interest to evaluate $T_{c.r.}$ according to data on the composition of the group of $L$ nuclei.

a certain degree.* In all probability, the magnetic fields in the Galaxy as a whole are very tangled. Thus the cosmic rays move along complex paths, and most of them spend their entire "lives" within the limits of the Galaxy.

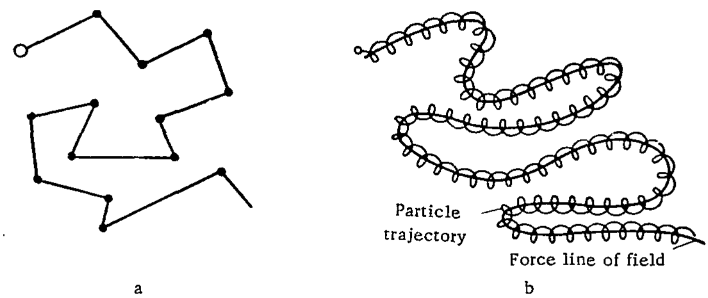


FIGURE 3. a) Motion of molecules in a gas; b) motion of particle in magnetic field.

Now let us return to the problem of the chemical composition of cosmic rays. One important conclusion follows from what was stated about the origin of $L$ nuclei. Since these nuclei are products of the disintegration of heavier nuclei, it is evident that there must be more heavy nuclei at the cosmic-ray sources than near the earth. In other words, compared with the composition near the earth, the chemical composition of the cosmic rays at their sources is considerably richer in "very heavy" ($VH$) nuclei, at the expense of protons, $\alpha$-particles, $L$ nuclei, and probably $M$ and $H$ nuclei as well. There are two things which could account for this. First of all, the cosmic-ray sources may in general be very rich in hydrogen, helium, and the other light and intermediate elements. This possibility cannot be rejected categorically, but it is the less probable one (the chemical composition of the sources need not, of course, be the same as the average composition of the material in the universe, but there is no known convincing evidence that it is radically different). The more likely possibility is that heavy nuclei are accelerated more efficiently than light nuclei in the cosmic-ray sources. The mechanism of the prevailing type of acceleration of heavy nuclei is known, and it will be discussed below. Consequently, this prevailing acceleration of heavy particles, together with certain properties of the chemical compositon of the gas in the sources, probably explains the observed cosmic-ray composition.

Aside from the data for groups of nuclei, some interesting data are now available on certain specific nuclei. For example, there are more carbon

* The successful application of the diffusion approximation depends on the following fact: in reality the particle trajectory is not "attached" firmly to the lines of force. A gradual transition from one line of force to another takes place, first because of the so-called "drift" in a nonuniform field, and second because under the conditions in the Galaxy a magnetic field constantly varies as a result of the galactic rotation and the movement of clouds of interstellar gas. Consequently, the cosmic rays in the Galaxy become mixed quite effectively, that is, their average motion is similar to that in the diffusion process.

nuclei in cosmic rays than oxygen nuclei, whereas, on the average, the opposite is true for the universe as a whole. Moreover, the most important of the *VH* nuclei are iron and chromium. The significance of independent determinations of the amounts of Li, Be, and B within the *L* group has already been mentioned as well as the fact that preliminary data in this direction have been gathered. Finally, information on the isotopic content of the helium in cosmic rays has been obtained recently. According to the latest (and therefore most reliable) data, $He^3/(He^3 + He^4) = 0.1$ to 0.2 (unfortunately, all these data pertain only to the low-energy range, from 80 to 350 Mev/nucleon). On the other hand, in nature $He^3$, the light isotope of helium (the $He_2^3$ nucleus consists of two protons and one neutron), only amounts to, on the average, about $10^{-6}$ of all the helium; thus the natural helium is almost all $He^4$. Once the ratio $He^3/(He^3 + He^4)$ has been specified more accurately, this information can be used for the same purposes as were the data for the *L* nuclei.

When discussing the chemical composition of cosmic rays, we have essentially referred to just the major portion of the cosmic rays, which have energies below $10^{12}$ to $10^{13}$ ev. Almost no reliable data are available on the chemical composition of cosmic rays with energies higher than this.

In addition to nuclei, cosmic rays also contain electrons, and probably positrons, $\gamma$-rays, and neutrinos as well. These components of cosmic rays will be discussed below.

## ENERGY SPECTRUM. ISOTROPY OF COSMIC RAYS

The cosmic-ray flux in the range of kinetic energies $\varepsilon_K > 1$ Bev/nucleon decreases monotonically and quite rapidly with a rise in energy (Figure 4). Let us designate the flux of particles of atomic weight $A$ and total energy* (per nucleon) greater than $\varepsilon$ as $I_A(>\varepsilon)$. The energy spectrum can then be represented approximately as

$$I_A(>\varepsilon) = \frac{K_A}{\varepsilon^{\gamma-1}}, \tag{2}$$

where for protons and all nuclei $\gamma = 2.5 \pm 0.2$ (according to other data, $\gamma = 2.7 \pm \pm 0.1$). Spectrum (2) is called the integral spectrum. The differential spectrum $I_A(\varepsilon) = (\gamma - 1)K_A\varepsilon^{-\gamma}$, since $I_A(>\varepsilon) = \int_\varepsilon^\infty I_A(\varepsilon)\,d\varepsilon$. For protons $K_p \approx 5000$ (energy $\varepsilon$ measured in Bev). Thus, in accordance with the data of Table 1, we have: $(I_p > 2.5$ Bev$) \approx 1300$ protons/m$^2$ ster sec. As mentioned above, the total flux $F = \pi I$, so that approximately 4000 protons per m$^2$ per second arrive at the earth.** The fluxes of all the other particles are also easy to obtain using formula (2) and Table 1.

* The total energy of a particle with a mass $M$ is $E = E_K + Mc^2 = A\varepsilon_K + AM_pc^2$, where $M_p$ is the mass of a proton (the difference between the mass of a proton and that of a neutron is negligible). Obviously, $\varepsilon = \varepsilon_K + 0.938$ Bev, since for a proton $M_pc^2 = 0.938$ Bev.

** Particles with $E = 2.5$ Bev can reach the earth just at quite high latitudes. Only protons with $E > 15$ Bev fall vertically and reach the equator. Their total flux $F \approx 220$ protons/m$^2$ sec.

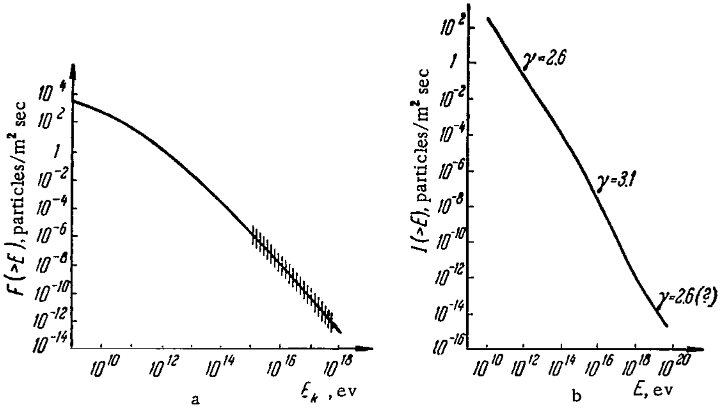


FIGURE 4. a) Total flux $F = \pi I$ of all cosmic rays with kinetic particle energies greater than $E_K$ (ev); b) flux $I$ ($> E$) according to more recent data.

The energy spectra of cosmic rays with low energies and very high energies are of special interest. For example, for relatively "soft" particles with kinetic energies $\varepsilon_K \lesssim 1$ Bev/nucleon, the spectrum is already not determined by expression (2). From the qualitative point of view, the change takes place because the flux stops increasing with a decrease in energy. This means that the curve (integral spectrum) for $I(>\varepsilon)$ reaches "saturation" (becomes horizontal), while the curve for $I(\varepsilon)$ (differential spectrum) passes through a maximum for some energy $\varepsilon_{K,\,max} < 1$ Bev/nucleon. This effect, an absence of low-energy particles in the primary cosmic rays near the earth, is called high-latitude cutoff of the spectrum: particles with $\varepsilon_K < 1$ Bev/nucleon should reach the earth only in quite high latitudes. The magnitude of $\varepsilon_{K,\,max}$, as well as the whole character of the high-latitude cutoff of the spectrum, depends on the solar-activity cycle. During the period of minimum solar activity, the high-latitude cutoff is less pronounced. On the other hand, at times when the sun is most active, when many spots are visible on its disk and gas flows, etc., are ejected, the high-latitude cutoff is very distinct. This fact leads us to conclude that the effect in question is caused by magnetic fields in the solar system. Such fields are "frozen into" the flow of "solar wind" (the stream of ionized gas ejected by the sun). Moreover, it is also possible that there exists in the solar system a quasiregular magnetic field, produced by currents moving through the interplanetary gas in the earth's orbital plane.

With respect to perturbations caused by the "solar wind," it is too soon to make any definite conclusions concerning the spectrum of low-energy cosmic rays far from the solar system. Preliminary results indicate, however, that for $\varepsilon_K > 10^8$ ev/nucleon no maximum exists in the differential spectrum of galactic cosmic rays. On the whole, the shape of the spectrum in the low-energy range is still unknown.

In addition to the high-latitude cutoff, the presence of magnetic fields in the solar systen causes variations in the cosmic-ray intensity. These variations are latitude-dependent and also depend on the height of the observation point above sea level; in general they are determined by the solar activity. It has also been established that the sun sometimes emits cosmic rays, mainly with comparatively low kinetic energies $E_k < (1 \text{ to } 3) \cdot 10^8$ ev. These particles fall only in the high latitudes; they were discovered in experiments with sounding balloons and satellites. Several powerful "bursts" of solar cosmic rays have also been recorded during the last twenty years. The most intense of these bursts occurred on 23 February 1956. At the time of this burst the cosmic-ray flux, even at the earth's surface (to say nothing of that at great heights), jumped to several times its normal level. For example, at Moscow the flux was four times as high; two hours after the onset of the burst, the flux increase had already dropped to only 20%. When other intense bursts were recorded, the peak flux at the earth increased by some tens of percent.

The study of solar cosmic rays and the effect which solar activity has on cosmic rays arriving from the Galaxy is now the subject of a research field which is very closely related to solar physics and interplanetary physics.*

Whereas "soft" cosmic rays give information about the sun and the solar fluxes, the study of very "hard" cosmic-ray particles is especially important for ascertaining the role played by cosmic rays of extragalactic origin. Unfortunately, it is quite difficult to make studies of cosmic rays with very high energies, and relatively few results have been obtained so far. The main reason for this is that the flux of high-energy particles is very small. Let us use expression (2) to describe the flux of all cosmic rays, with $K$ = 5000 and $\gamma = 2.5$, and with the energy $\varepsilon$ per nucleon replaced by the total particle energy $E$. The fluxes of particles with energies $E$ greater than $10^{15}$, $10^{17}$, and $10^{19}$ ev (that is, $10^6$, $10^8$, and $10^{10}$ Bev) will then be, respectively,

$$I(E > 10^6\,\text{Bev}) = 5 \cdot 10^{-6}, \quad I(E > 10^8\,\text{Bev}) = 5 \cdot 10^{-9},$$
$$I(E > 10^{10}\,\text{Bev}) = 5 \cdot 10^{-12} \text{ particles/m}^2 \text{ ster sec.} \tag{3}$$

There are about $3 \cdot 10^7$ seconds in a year, and a particle with an energy greater than $10^{19}$ ev should arrive at any 1 $m^2$ of the earth's surface (from all directions) on the average once every 2000 years! Actually, the flux of particles with very high energies is considerably lower even than this, since power law (2) is valid only within a limited energy range and the spectrum falls more sharply with a rise in energy than according to (2) with $\gamma = 2.5$ (the best data known to us give $\gamma = 3.1 \pm 0.1$ for $E > 10^{15}$ ev; see also Figure 4).

In spite of the foregoing, particles with energies as high as $10^{20}$ ev have been detected. These were found during observations of extensive air showers. Cosmic rays with energies above $10^{14}$ to $10^{15}$ ev are only studied using the method of extensive showers. Extensive showers are formed as follows. A high-energy proton or nucleus entering the atmosphere collides with N and O nuclei, producing a large number of high-energy particles (nucleons emitted by the N and O nuclei, nucleon-antinucleon pairs, hyperons, K and $\pi$ mesons). These particles in turn split up other nuclei or else decay (for ex-

* Such problems will not be treated here in greater detail. For further discussion of the subject, see DORMAN, L.I. Variatsii kosmicheskikh luchei i issledovanie kosmosa (Cosmic-Ray Variations and Space Research). —Izdatel'stvo Akademii Nauk SSSR. 1963.

ample, $\pi^{\pm}\to\mu^{\pm}+\nu$ or $\mu^{\pm}\to e^{\pm}+\nu+\bar{\nu}$ decays take place).* As a result of such a cascade, an extensive shower containing an enormous number of particles is produced in the atmosphere (in the vicinity of the earth's surface, the shower mainly consists of electrons, positrons, and hard photons). The area of effective shower recording, for instance using a system of counters, depends on the energy of the primary particle and may reach many square kilometers. Showers are observed and studied using systems of counters of various types, spread out over a large area and connected "in coincidence." A counter system makes it possible to record particles falling onto a large area, and this takes place quite frequently. For example, a particle with $E > 10^{19}$ ev falls onto a surface $10\,km^2$ in area once every few days.

Consequently, extensive-shower observations enable us to record even such rare cosmic-ray events as the falling of particles with energies from $10^{18}$ to $10^{20}$ ev. However, quite a high price must be "paid" for this. First of all, the energy of the primary particle cannot be determined very accurately. Second, and this is the main thing, it is not possible to ascertain what kind of particle (proton or some nucleus) caused the shower. Therefore, in regions where cosmic rays are studied only in showers, the chemical composition of the cosmic rays cannot be reliably ascertained. If this compostion is the same as that of low-energy cosmic rays, then somewhat more than half of all the showers with total energies greater than that specified are produced by nuclei rather than protons. It may be that all the particles with energies higher than, say, $10^{17}$ ev are nuclei of the iron or chromium type. Then the energy per nucleon will be only about 1/50 of the total particle energy. This is very important with respect to ascertaining the origins of particles with very high energies. The thing is that, for a $10^{19}$-ev proton, the radius of curvature of the trajectory in a field of 10 oersteds is $3 \cdot 10^{21}$ cm, which is a distance comparable with the radius of the Galaxy ($3 \cdot 10^{22}$ to $5 \cdot 10^{22}$ cm). An iron nucleus ($Z = 26$) with this same total energy follows a trajectory with a curvature radius which is 1/26 as long (about $10^{20}$ cm). Such a nucleus will, in all likelihood, have a galactic origin and remain in the Galaxy. Protons with $E > 3 \cdot 10^{18}$ to $10^{19}$, on the other hand, will obviously not stay within the Galaxy and must have originated somewhere beyond its limits.

As mentioned above, we do not yet have any reliable data on the chemical composition of cosmic rays with very high energies ($E > 10^{18}$ ev). Preliminary data indicate, however, that such particles having ultrahigh energies can hardly consist just of heavy nuclei. Moreover, even heavy nuclei with energies higher than $10^{19}$ ev (and also particles with $E \lesssim 10^{20}$ ev, a very small number of these having been observed) probably do not remain within the limits of the Galaxy to any extent. Therefore, it is most likely that cosmic rays with ultrahigh energies are made up of particles of extragalactic origin. Let us call such cosmic rays originating beyond the limits of our Galaxy "metagalactic" cosmic rays. These may have been accelerated in certain other galaxies, specifically in radio galaxies, where cosmic-ray generation takes place especially intensively and effectively. This will be discussed further below.

* Here, the usual notation for $\pi$ mesons, $\mu$ mesons, electrons, and neutrinos is used ($\pi$, $\mu$, e, and $\nu$); antineutrinos are designated as $\bar{\nu}$, and the $\pm$ signs indicate the charge of the particles.

Whereas particles with ultrahigh energies follow trajectories having radii of curvature comparable to the dimensions of the Galaxy, for most cosmic rays the radius of curvature is undoubtedly negligible in comparison with the distance to the nearest stars. For example, we have already noted that a $10^{10}$-ev proton in a field of $10^{-6}$ oersted will follow a trajectory with a curvature radius of $3 \cdot 10^{13}$ cm. The nearest star, on the other hand, is about 4 light years, or $4 \cdot 10^{18}$ cm, away.

The smallness of the radii of curvature of cosmic rays, as well as the irregularity and random nature of the interstellar magnetic fields and some other factors, are responsible for the isotropy of cosmic radiation. Quantitatively, the degree of anisotropy can be characterized by the coefficient $\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$, where $I_{max}$ and $I_{min}$ are the maximum and minimum cosmic-ray fluxes beyond the range of action of the earth's magnetic field. The flux far away from the earth can be estimated from measurements in the vicinity of the earth, since the nature of the particle motion in the earth's magnetic field is known. Let us recall too that $I$ is the flux in some direction (intensity), so that $I_{max}$, for example, is the flux in the direction in which $I$ is a maximum. According to available data for particles with $E < 10^{16}$ ev, the coefficient $\delta < 1\%$. For energies higher than this the measurement accuracy is lower, but within the limits of the attainable accuracy no anisotropy of the primary cosmic rays has been observed.

## ELECTRONS AND POSITRONS

On the basis of general considerations, it has been clear for a long time that primary cosmic rays must contain a certain number of electrons and positrons, in addition to protons and nuclei. Actually, when cosmic-ray protons and nuclei collide with the nuclei of atoms of the interstellar medium, a certain number of $\pi^{\pm}$ mesons are produced, and as a result of $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ and $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$ decays electrons $e^-$ and positrons $e^+$ are produced. In addition, it can be assumed that electrons are accelerated at the cosmic-ray sources as well as protons and nuclei. Finally, radio-astronomical data, which will be discussed in the next chapter, show convincingly that relativistic electrons, which produce the electron component* of cosmic rays, actually do exist in interstellar space.

Evaluations of the number of secondary electrons (products of $\pi \rightarrow \mu \rightarrow e$ decay), together with radio-astronomical observations, indicate that the cosmic-ray electron flux amounts to only a few percent of the proton-nucleus flux. This fact, the smallness of the flux, explains why the electron component of the primary cosmic rays was only discovered in 1961, and also why the data obtained for this component are still comparatively sparse.

The flux of electrons with $E > 1$ Bev constitutes about 1.5% of the flux of all cosmic rays with $E_K \gtrsim 1$ Bev. In the energy range from 1 to 10 Bev the

* In most cases (especially in radio-astronomical observations) the total number of electrons and positrons is determined. Consequently, it would be more accurate to speak of the "electron-positron component." However, for the sake of brevity, we refer to both electrons and positrons as the "electron component" or "relativistic electrons," except when these particles are actually considered separately.

electron spectrum is described by the expression

$$I_e(E)=40\cdot E^{-2}\frac{\text{electrons}}{\text{m}^2\ \text{ster sec Bev}}. \tag{4}$$

For $E>10$ Bev the spectrum drops more sharply, so that index $\gamma$ is from 2.5 to 2.7, instead of the value $\gamma=2$ in (4). If spectrum (4) is used for all energies $E>1$ Bev anyway, then

$$I_e(>E)=\int_E^\infty I(E)\,dE=40\cdot E^{-1}\ \text{electrons/m}^2\ \text{ster sec},$$

where $E$ is measured in Bev. Here it must be remembered that the accuracy of expression (4) is low and that the data of different investigators differ quite considerably.

The first measurements of the composition of the electron component were published in 1964 (that is, the component was divided into electrons and positrons). For the energy range $0.3\leqslant E\leqslant 1$ Bev, the best value obtained so far for the ratio of the positron flux $I_{e+}$ to the total flux $I_{e-}+I_{e+}$ of the electron component is: $I_{e+}/(I_{e-}+I_{e+})=0.20\pm0.15$. However, it should be remembered that these measurements were made with balloons, so that there was an air layer about $4\,\text{g/cm}^2$ thick above the equipment. Consequently, some of the electrons and positrons could have been secondary. The provisional conclusion might thus be made that positrons constitute less than 20% of the total cosmic-ray electron component near the earth (in the range $0.3\leqslant \leqslant E\leqslant 1$ Bev).* Even such a modest conclusion as this is apparently very significant. This is because a secondary origin of the electron component, that is, the creation of this component in interstellar space as a result of nuclear collisions and consequent $\pi\rightarrow\mu\rightarrow e$ decay, would produce many positrons. Calculations show that in this case a value of $I_{e+}/(I_{e-}+I_{e+})\approx 0.65$ should be expected; in any case it will be true that $I_{e+}/(I_{e-}+I_{e+})>0.5$. Thus it may be concluded that the cosmic-ray electron component is mostly generated in certain sources, probably together with and at the same time as the proton-nuclear component.

Only charged particles of cosmic origin which have kinetic energies greater than, say, 100 Mev will here be considered to be cosmic rays (particles with lower energies, but which still exceed those of most particles in the interplanetary gas, are sometimes called subcosmic). It should not be forgotten, however, that there are uncharged high-energy particles arriving from space which are closely related to cosmic rays. Here, we are referring mainly to the hard electromagnetic radiation (in quantum language, the hard photons) which produce x-rays and gamma rays.

In addition to these rays (which will be treated in a later chapter), there are also neutrinos arriving from outer space. It is extremely difficult to record the latter, because of their exceptionally high penetrating power. Nevertheless, it is to be expected that in the near future the nascent science

* This conclusion was confirmed and the data made more accurate as a result of measurements which became known to us early in 1967. According to these data, for example for $1<E<5$ Bev, the ratio $I_{e+}/(I_{e-}+I_{e+})=0.08\pm0.04$

of neutrino astronomy will achieve its first success: to record and to investigate the neutrino emission of the sun, which is ejected close to the solar center by very hot regions there (as far as we know, no science-fiction writer has ever predicted that man would be able to peer into the very depths of the solar interior, which is now already quite feasible as a result of advances in neutrino physics).

Solar neutrinos are produced in the nuclear reactions which "heat up" the sun, and they are in no way related to cosmic rays (consequently, they will not be treated in more detail here). On the other hand, the neutrinos $\nu$ (and antineutrinos $\bar{\nu}$) originating as a consequence of the above-mentioned $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ and $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$ decays in interstellar space are directly related to cosmic rays, and in fact are generated by them. Calculations show that the flux of such secondary neutrinos with energies above 1 Bev is $I_{\nu}(E > 1\ \mathrm{Bev}) \lesssim 1$ neutrino/m$^2$ ster sec. The observation of this flux is not only extremely difficult in itself, but is also made practically impossible by the fact that cosmic rays produce from a hundred to a thousand times more neutrinos in the earth's atmosphere than in interstellar space.* Consequently, only if the neutrino flux in interstellar space should happen to be considerably higher than the flux of secondary neutrinos, for some reason or other, could we expect to record the cosmic neutrinos and determine their energy spectrum. In the middle of 1965 the first reports were received stating that high-energy neutrinos has been detected in two underground laboratories. It is most likely that these neutrinos were produced by cosmic rays in the atmosphere; in any case, such an assumption cannot now be refuted.

* At present cosmic neutrinos can be recorded only deep underground, because of the unwieldiness of the equipment and, mainly, because it is necessary to "block out" the background of charged particles. Therefore, neutrinos produced in the atmosphere are also picked up by the measuring equipment.

*Chapter 2*

## *RADIO ASTRONOMY AND COSMIC RAYS*

As we mentioned in the introduction, until recently the only source of information about the cosmos was the visible radiation emitted by the sun, stars, galaxies, etc. Now, however, the study of cosmic radio emission, which is the basic task of radio astronomy, has become an equally important method. Cosmic radio emission reaching the earth from our Galaxy was discovered in 1931-1932. Solar radio emission was observed in 1942-1943. However, up until 1945 only a few radio-astronomical studies were published, and it was only in recent years that radio astronomy began to develop intensively. The latter development has resulted in some very important discoveries. At present radio methods are on a par with optical techniques, and important problems (such as those of solar physics) are studied simultaneously using both methods. Consequently, the separation of astronomy into optical astronomy and radio astronomy is becoming, to an ever-increasing extent, a methodical distinction, rather than indicating a difference in the object of study. It is noteworthy that, after only about 25 years of development, radio astronomy has become nearly as important as optical astronomy, which came into being in ancient times. In the subsequent discussion, the nature of cosmic radio emission and the "radio map" of the sky will be of special importance.

### THE NATURE OF COSMIC RADIO EMISSION

The cosmic radio emission which is picked up on earth can be divided into three components: thermal emission with a continuous spectrum; thermal emission of neutral hydrogen with a wavelength of about 21 cm, and also emission of hydrogen atoms and hydroxyl (OH) molecules with various different wavelengths; and nonthermal cosmic radio emission. The first of these components is a kind of bremsstrahlung of the electrons of the interstellar medium, occurring when these electrons collide with ions. The intensity of this emission will naturally be especially high from regions where the gas temperature and the degree of gas ionization are high, as is the case, for example, in the vicinity of very hot stars. Some regions of the atmospheres of various types of stars are also strongly heated, including stars like our sun which are not very hot. The only thermal radio emission from a stellar atmosphere which can be picked up on the earth is from the sun. In the subsequent treatment of cosmic radio emission, only emission originating beyond the limits of the solar system will be referred to.

The temperature of ionized gas in our Galaxy does not exceed $10^4$ degrees; this will be the maximum temperature of the thermal radio emission emanating from this gas. *

Monochromatic cosmic radio emission of neutral hydrogen ($\lambda = 21$ cm) was discovered in 1951. This radiation is also essentially thermal (equilibrium) emission, even though its temperature doen not usually exceed 100°K. Radiation with a wavelength of 21 cm is emitted during transitions between sublevels of the hyperfine structure of the hydrogen-atom ground level. These sublevels correspond to the two possible mutual spin orientations of the electron and proton making up the hydrogen atom.

Before the $\lambda = 21$ cm spectral line could be picked up, it was possible to obtain information only concerning light-emitting excited hydrogen atoms. Naturally, there are an incomparably greater number of unexcited atoms than excited ones. In fact, in many parts of the sky there are so few excited atoms that their emission is imperceptible. Moreover, the luminous emission is greatly scattered and absorbed by interstellar (cosmic) dust. Radio waves, on the other hand, are scattered and absorbed incomparably less by dust. Thus, reception of the 21-cm radio emission was exceptionally important to astronomers, since it enabled them to make the first really detailed studies of the spiral structure and central regions of our Galaxy.

The third component of the cosmic radio emission, nonthermal emission with a continuous spectrum, is the one which is the most significant for our purposes. This radiation comes to us from every direction, from the Galaxy as a whole, from individual nebulae in the Galaxy, and from other galaxies. It is quite easy to show that a considerable part of the cosmic radio emission is nonthermal. This follows directly from the fact that the received radiation with wavelengths longer than several meters has a very high intensity. For example, the effective temperature of 16-meter cosmic radio emission may be as much as $3 \cdot 10^5$ °K, while that of radiation with a wavelength of around 30 meters may be $10^6$ °K. ** On the other hand, as mentioned above, the effective temperature of the thermal emission of the interstellar gas cannot exceed the temperature of this gas (about $10^4$ °K).

Thus it is certain that some intense nonthermal cosmic radio emission exists. Moreover, this radiation is in most cases the predominant part of the cosmic radio emission.

* The intensity $I$ (flux in a given direction) of the thermal emission of a medium with a temperature $T$ is

$$I_\nu = \frac{2k\nu^2}{c^2} T_{\text{eff}}, \quad T_{\text{eff}} = T(1 - e^{-\tau}), \qquad (5)$$

where $\nu = c/\lambda$ is the emission frequency, $\lambda$ is the wavelength, $c = 3 \cdot 10^{10}$ cm/sec is the speed of light in a vacuum (and in practice in a sufficiently rarefied gas as well), $\tau$ is the optical thickness of the medium, which characterizes the absorption of the given radiation as it propagates through the medium (in (5) it is taken into account that $h\nu \ll kT$, where $h = 6.625 \cdot 10^{-27}$ erg sec is Planck's constant, and $k = 1.38 \cdot 10^{-16}$ erg/deg is Boltzmann's constant). From formula (5) it is evident that the effective temperature $T_{\text{eff}} \leqslant T$.

** The intensity $I_\nu$ of any radio emission with a specified frequency $\nu$ can be characterized by the effective temperature $T_{\text{eff}}$, determined using the formula

$$I_\nu = \frac{2k\nu^2}{c^2} T_{\text{eff}} = \frac{2k}{\lambda^2} T_{\text{eff}}$$

(see (5)). It should be noted that for electromagnetic waves it is customary to use the term "intensity," rather than "flux."

Let us next discuss the nature of the nonthermal cosmic radio emission. This very important problem was not solved without some difficulty. For quite a long time the nonthermal radio emission was thought to be generated in the shells of an enormous number of hypothetical radio stars, which possessed unusual properties and were not observed in the optical part of the spectrum. Since this assumption has now been abandoned, it will not be treated in greater detail here.

Another explanation of the origin of nonthermal cosmic radio emission, which has since been found to be correct, was suggested and developed between 1950 and 1953. It may be summed up in the statement that the nonthermal cosmic radio emission is actually a magnetic bremsstrahlung (synchrotron radiation) of the relativistic electrons making up the cosmic-ray electron component.* With respect to this, a surprising relation was established between radio emission and cosmic rays: most of the cosmic radio emission is generated by cosmic rays!

Therefore, radio astronomy provides us with a means of studying cosmic rays throughout the universe. In addition, it brings us very near to a solution of the problem of the origin of cosmic rays. It is interesting to note that the bremsstrahlung theory of cosmic radio emission was by no means immediately accepted as widely as it is at present. In fact, a paper dealing with this theory, presented at the Manchester Symposium on Radio Astronomy in 1955, was not even published in the proceedings of the symposium. On the other hand, the proceedings which appeared in 1957 included a report relating the nonthermal radio emission to the hypothesis on the existence of an enormous number of radio stars.

Before going on to discuss the results of the radio-astronomical studies, let us consider the special features of the magnetic-bremsstrahlung mechanism. A charged particle moving in a magnetic field of intensity $H$, just as in the case of any nonuniform motion, emits electromagnetic waves. The angular frequencies of the emitted waves for circular motion, will equal the angular frequency $\omega_H^*$ of particle rotation in the magnetic field and its harmonics $n\omega_H^*$, where $n$ is any whole number. To be specific, let us sider an electron, for which

$$\omega_H^* = \frac{eH}{mc^2}\frac{mc^2}{E} = 1.76 \cdot 10^7 H \frac{mc^2}{E}, \tag{6}$$

where $E$ is the total energy of the electron, and $mc^2 = 5.1 \cdot 10^5$ ev is its rest mass.

A nonrelativistic electron (for which $(E-mc^2) \ll mc^2$) emits almost exclusively the fundamental frequency $\omega_H^* \approx \omega_H = eH/mc$; the nature of this radiation is the same as that of the radiation emitted by two mutually perpendicular dipoles whose oscillation phases are shifted by 90°. However, in the ultra-

* Let us stress that here we are not referring to all the nonthermal cosmic radio emission, but only to the most important part of it, which emanates from the interstellar space of our Galaxy and from various nebulae (envelopes of supernovae, "normal" galaxies, and radio galaxies; see below). Solar radiation includes not only magnetic-bremsstrahlung type nonthermal radio emission, but also nonthermal radio emission of another type, which can be called coherent plasma radio emission (it appears only in regions where a sufficiently dense plasma (ionized gas) exists). Coherent plasma radio emission is probably also produced at the time of eruptions (outbursts) on so-called flaring stars, on quasars, and in the "compact" radio source in the Crab Nebula (see below).

relativistic case of interest to us, when $E \gg mc^2$, the particle emits waves predominantly in the direction of its instantaneous velocity, and the radiation is concentrated within a narrow cone with an aperture angle $\theta \sim mc^2/E \ll 1$.

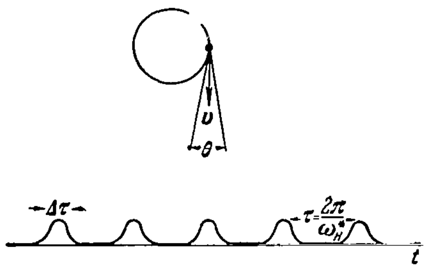


FIGURE 5. Magnetic bremsstrahlung (synchrotron radiation).

Particle moves around circle with velocity $v$ $(v \approx c)$ and angular velocity $\omega_H^* = \frac{eH}{mc}\frac{mc^2}{E}$. Lower part of diagram shows curve for intensity of radiation recorded by instrument located in orbital plane of particle.

Therefore, if the electron moves in a circle (this takes place if its velocity $\boldsymbol{v}$ is at right angles to the field $\boldsymbol{H}$), electromagnetic waves are emitted like the sparks from a grindstone when a knife is being sharpened. In other words, an observer in the orbital plane records bursts of radiation by time intervals of $\tau = 2\pi/\omega_H^*$ (Figure 5). The duration of each burst will be $\Delta\tau \sim \frac{r\theta}{c}\left(\frac{mc^2}{E}\right)^2 \sim \left(\frac{mc}{eH}\right)\left(\frac{mc^2}{E}\right)^2$, where $r = \frac{c}{\omega_H^*}$ is the radius of the orbit, and the factor $(mc^2/E)^2$ takes into account the Doppler effect. Since the radiation is periodic (with a period $\tau = 2\pi/\omega_H^*$), its frequency spectrum, as noted above, will consist of harmonics of the frequency $\omega_H^*$. Frequencies of the order of $\frac{1}{\Delta\tau} \sim \omega_m = \left(\frac{eH}{mc}\right)\left(\frac{E}{mc^2}\right)^2$, corresponding to the characteristic burst duration $\Delta\tau$, will be associated with a maximum intensity. For an electron with an energy $E$ equal to, for example, $5 \cdot 10^8$ ev in a field $H = 10^{-5}$ oersted, the frequency $\omega_H^* = 0.176$ sec$^{-1}$ and the frequency $\omega_m \sim 10^8$ sec$^{-1}$. Consequently, the very high harmonics $\omega_m = n_m \omega_H^*$ will appear in the spectrum, where in our example $n_m \sim 10^9$. In a case like this, obviously, the spectrum will be so "dense" that it is practically continuous (Figure 6).

The energy $P(\nu, E)$ emitted by an electron in one second in the frequency interval $d\nu = d\omega/2\pi$ is

$$P(\nu,\ E) = 16\frac{e^3 H_\perp}{mc^2}\, p\left(\frac{\omega}{\omega_m}\right), \quad \omega_m = \left(\frac{eH_\perp}{mc}\right)\left(\frac{E}{mc^2}\right)^2; \qquad (7)$$

the function $p(\omega/\omega_{\max})$ is shown is Figure 6.

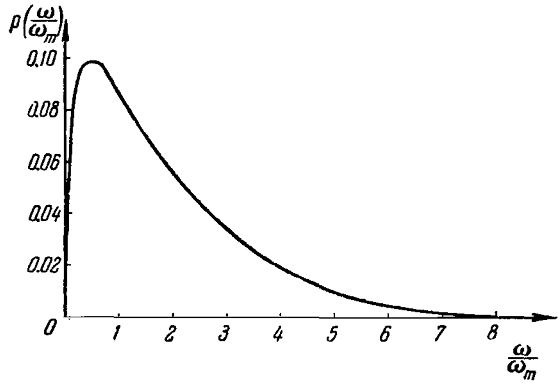


FIGURE 6. Spectrum of magnetic bremsstrahlung.

Maximum emission corresponds to a frequency $\nu_{max}$ and an energy $P(\nu_{max}, E)$, equal to

$$\nu_{max} = 0.43\frac{\omega_m}{2\pi} = 1.2 \cdot 10^6 H_\perp \left(\frac{E}{mc^2}\right)^2 \text{ cps}, \tag{8}$$

$$P(\nu_{max}, E) = 1.6\frac{eH_\perp}{mc^2} = 2.16 \cdot 10^{-22} H_\perp \frac{\text{erg}}{\text{sec cps}}. \tag{9}$$

The quantity $H_\perp$ entering into these formulas is the component of $\boldsymbol{H}$ normal to the particle velocity $\boldsymbol{v}$. This component $H_\perp$ appears in the formulas for the general case of helical motion of a particle.

It has been established that magnetic fields with intensities $H \sim 10^{-6}$ to $10^{-5}$ oersted exist in interstellar space. If $H_\perp \sim 3 \cdot 10^{-6}$ oersted and $E \sim 5$ $5 \cdot 10^9$ ev, then $\nu_{max} \sim 4 \cdot 10^8$ cps and the corresponding wavelength $\lambda_{max} = c/\nu_{max} \sim$ $\sim 0.7$ meter. From this example it is clear that in interstellar space cosmic-ray electrons with energies from $10^8$ to $10^{10}$ ev will produce magnetic bremsstrahlung in the radio range. The intensity of this radio emission can be evaluated simply using formula (9). Such an evaluation shows that, to explain the observed nonthermal radio emission in interstellar space, it is sufficient that in the Galaxy the flux $I_e(E>1\,\text{Bev})$ of electrons with energies greater than $10^9$ ev $= 1$ Bev be of the order of 10 electrons/m$^2$ ster sec. This amount constitutes about 1% of the entire cosmic-ray flux near the earth, and, as noted above, agrees with existing data on the flux of electrons and positrons in the space around the earth.

The magnetic bremsstrahlung is almost completely polarized, in that the electric vector in the wave is perpendicular to the magnetic field and the particle-velocity vector. The observed galactic radio emission, however, is only slightly polarized in the meter-wave range. There are two reasons for this: first, on a line of sight passing through the Galaxy, the magnetic field has a different orientation in different places, so that the total emission will already be depolarized somewhat. Second, under the influence of the magnetic field, the plane of polarization of the radio waves rotates in the interstellar medium, * and this also leads to depolarization of the radio emission. As a result, the cosmic magnetic bremsstrahlung is strongly polarized only in special cases, which will be discussed below.

The spectrum of electrons in the cosmos, at least within a limited energy range, may be assumed to be exponential. Thus the concentration of electrons with energies between $E$ and $E+dE$, will be $N_e(E)dE$, where

$$N_e(E)=\frac{K_e}{E^\gamma}. \tag{10}$$

For relativistic particles, as noted previously, the flux $I(E)=\frac{c}{4\pi}N(E)$ and $I(>E)=\frac{c}{4\pi}\int_E^\infty N(E)\,dE$. Therefore, the flux of electrons with spectrum (10) is $I_e(>E)=\frac{cK_e}{4\pi(\gamma-1)E^{\gamma-1}}$. For cosmic electrons with spectrum (10) the intensity of the radio emission has the form

$$I_\nu=\frac{2k\nu^2}{c^2}T_{\text{eff}}=1.35\cdot 10^{-22}a(\gamma)K_eRH^{\frac{\gamma+1}{2}}\left(\frac{6.26\cdot 10^{18}}{\nu}\right)^{\frac{\gamma-1}{2}}, \tag{11}$$

where $I_\nu$ is measured in

$$\frac{\text{erg}}{\text{cm}^2\cdot\text{ster}\cdot\text{sec}\cdot\text{cps}}=10^{-3}\,\text{w/m}^2\cdot\text{ster}\cdot\text{cps},$$

$R$ is the extent of the emitting region along the line of sight, $H$ is the mean magnetic-field intensity along the line of sight (the field is assumed to be directed randomly, on the average, so that its radiation is unpolarized), and $a(\gamma)$ is a comparatively slowly varying function of $\gamma$ (for instance, $a(1)=$ $=0.283$, $a(2)=0.103$, and $a(3)=0.074$).

If observations indicate that the intensity $I_\nu$ is proportional to $\nu^{-\alpha}$, then according to (11) the exponent $\gamma$ in (10) can be determined directly:

$$\gamma=2\alpha+1,\quad I_\nu=\text{const}\cdot\nu^{-\alpha}. \tag{12}$$

From the value of $I_\nu$ it is possible to find the product $K_eRH^{\frac{\gamma+1}{2}}$ and then to evaluate $K_e$, since the values of $R$ and $H$ are usually known, albeit roughly. Consequently, from the intensity of the cosmic radio emission, and from the dependence of this emission on frequency and observation direction, information can be obtained on the electron component of cosmic rays both in our Galaxy and in very distant galaxies.

* For a tenuous ionized medium, the effect of rotation of the polarization plane in a very weak field turns out to be considerable, due to the enormous extent of the interstellar magnetic fields. The magnetic radio bremsstrahlung in the interstellar medium can usually be considered to be the same as that for the motion of an electron in a vacuum, since the refractive index of the medium in this case is close to unity.

## RADIO TELESCOPES

The development of radio astronomy and the advances made in this field were accompanied by the development of instruments for picking up cosmic radio emission. These devices are generally referred to as radio telescopes, although sometimes this term is restricted to receiving antennas only, especially when they consist of parabolic or spherical reflectors. We do not intend to treat the operation principles and construction of radio telescopes here. However, the remarkable successes that have been achieved with these instruments in a comparatively short time should be noted.

Any telescope (radio, optical, x-ray, etc.) can be characterized by two main parameters: sensitivity (reception range) and angular resolving power. The greater the area of the receiving device (antenna or reflector), and the more sensitive the recording apparatus (photographic plate, electron or photomultiplier, radio receiver, x-ray and gamma-ray counters, etc.), the higher the sensitivity of a telescope will be. The angular resolution of a given telescope is the angular distance on the celestial sphere between the closest objects (for instance, stars) or details of a single object (for instance, parts of a planet) which can be mutually distinguished. This quantity is determined primarily by the ratio $\lambda/D$, where $\lambda$ is the wavelength, and $D$ is the reflector diameter or a characteristic dimension of the antenna. *

The largest existing optical telescope has a mirror with a diameter of 5 meters. Consequently, in this telescope light is gathered from an area of about $20\,m^2$, and the theoretical angular resolution $\lambda/D = 10^{-7} \approx 0.02''$ for typical visible waves with $\lambda = 5 \cdot 10^{-5}\,cm = 0.5$ micron. Unfortunately, the actual angular resolution is some tens of times worse than this and usually does not exceed $1''$, as a result of "noise" caused by the terrestrial atmosphere (the air above the mirror is nonuniformly heated, constantly moves, etc.). With a resolution of about $1''$, we could see a tall man from 350 km away, or else a matchbox from 10 km away.

Modern radio telescopes can gather radiation from areas of hundreds of square meters for the millimeter and centimeter ranges and many thousands of square meters in the meter range. For example, the area of the first-class millimeter-range radio telescope at the radio-astronomical station of the Physics Institute of the USSR Academy of Sciences near Serpukhov (see Figure 7) is $380\,m^2$ (diameter of 22 m). One of the best parabolic radio telescopes, which began operating in 1961 in Australia (see Figure 8), has a reflector with a diameter $D = 65$ m and it gathers radio waves from an area of about $3300\,m^2$. However, even for waves which are very short for radio astronomy ($\lambda = 10$ cm), the angular resolution of this telescope is only about $300'' = 5'$. Moreover, the resolving power of a gigantic instrument like this is only about $1°$ in the meter range. This means that in the meter range this radio telescope cannot even resolve large details on the sun or on the moon (the sun and moon, as visible from the earth, describe angles of about $30' = 0.5°$). However, at the beginning of the development of radio astronomy, even such a resolution seemed fantastic, since the antennas and

* With an accuracy up to nearly a unit of the multiplying factor, the ratio $\lambda/D$ equals the angle of divergence of the electromagnetic waves in the telescope as a result of diffraction (for example, diffraction at the edges of the reflector).

reflectors used then had dimensions which were only a few times greater than the wavelength. The areas of the reflectors and antennas were some tens of square meters, which is quite small, taking into account the exceptionally weak flux of cosmic radio emission reaching the earth. But numbers say very little, so as an illustration let us cite a method used in the summer of 1965 at a display at the Mullard Radio-Astronomical Observatory near Cambridge (England). Visitors at the display were led to a stand, where they were asked to take a small leaflet from a pile on the table. When he turned it over, the visitor read the following: "by taking this piece of paper from the table, you expended more energy than that expended by all the radio telescopes in the world throughout the entire history of radio astronomy."

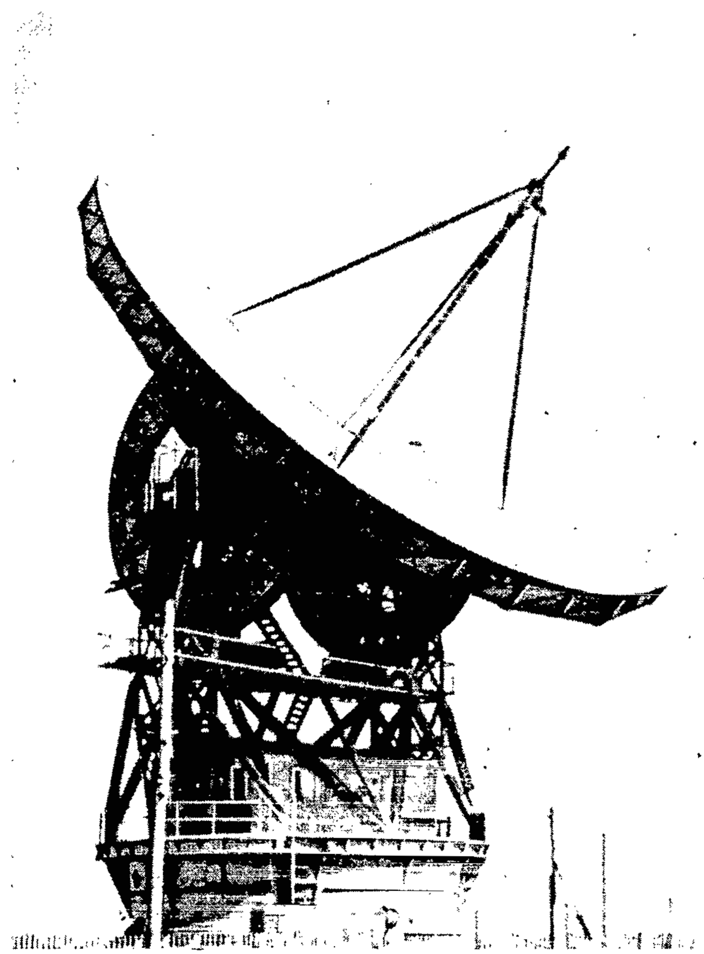

FIGURE 7. Radio telescope operating in millimeter range, reflector diameter 22 m (USSR).

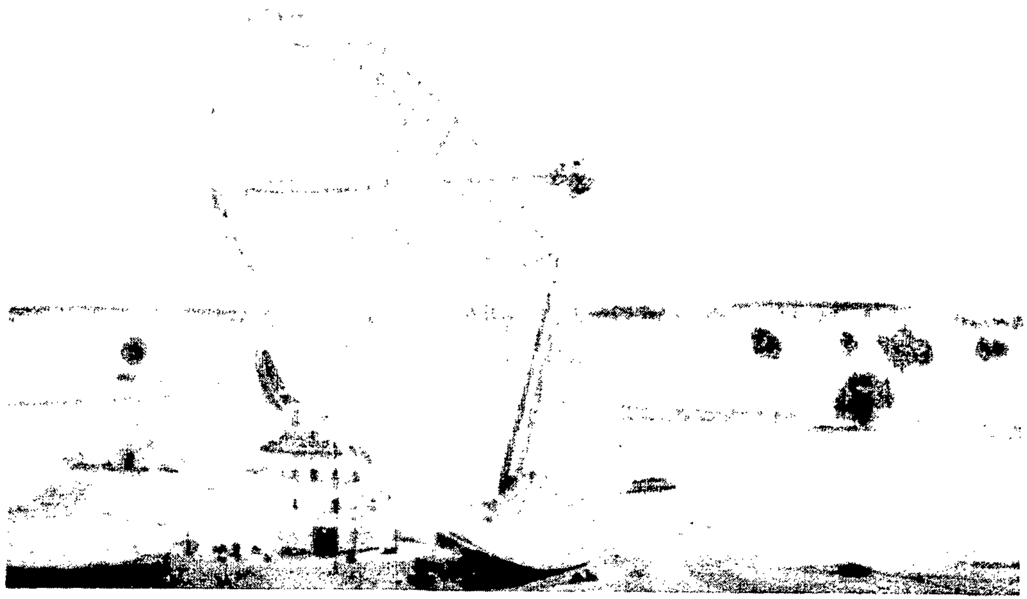

FIGURE 8. Radio telescope with reflector diameter of 65 m (Australia).

Therefore, even in the case of the largest radio telescopes, which gather cosmic radio emission from areas of thousands of square meters, the sensitivity attained by the receiving apparatus is amazing. This sensitivity is so high that radio telescopes can now pick up waves emitted by the furthest galaxies, lying several billion light years away (a light year equals $10^{18}$ cm; it takes light 8 minutes to get from the sun to the earth, so this distance is equal to 8 light minutes).

In general the sensitivity of a modern radio telescope is not inferior to, and sometimes may even exceed, that of an optical telescope. The same is true of the angular resolution of the telescope, but with the following reservation: a high resolution can be obtained in the radio range only with the use of special instruments or under special conditions, which introduces certain complications. Let us now discuss these special instruments or conditions.

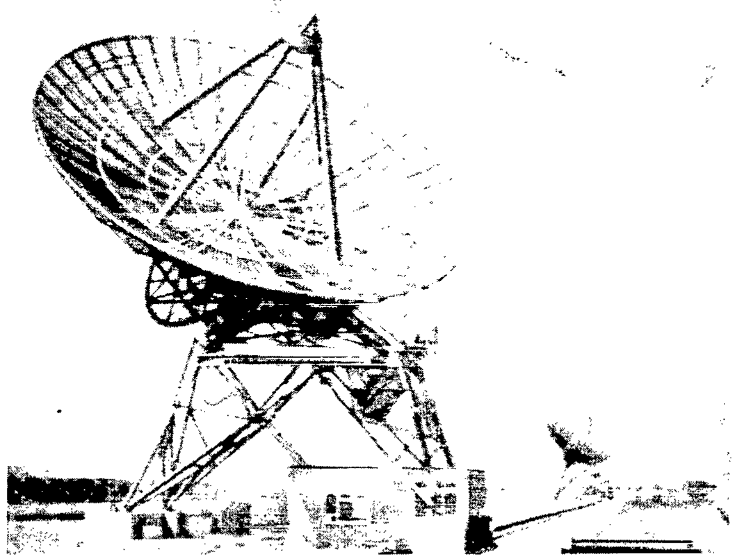

FIGURE 9. Radio interferometer (England).

In general, interferometers are constructed to increase the angular resolution. This means that two or more comparatively small reflectors (antennas), separated by a strictly specified distance $L$, are used. The sensitivity of such a system is, as in the previous case, determined primarily by the reflector area. The angular resolution, however, is characterized mainly by the ratio $\lambda/L$, rather than just by $\lambda/D$ (where $D$ is the reflector diameter). In the meter range the "baseline" $L$ of existing interoferometers reaches tens or even hundreds of kilometers. For example, for 5-meter waves and a base of 50 km, the ratio $\lambda/L \sim 10^{-4} \approx 20''$. Actually, in this way resolutions of the order of $1''$ have already been attained (that is, the same as in optical astronomy). One of the best and most unique interferometers in the world recently began operating at the above-mentioned radio observatory near Cambridge. Two of the three reflectors of this interferometer (the diameter of each reflector is about 20 m; they operate in the range of $\lambda \geqslant 21$ cm) are shown in Figure 9. One of the reflectors moves along rails about a kilometer in length, its position being specified to within 3 mm. Such a high accuracy requirement is only one facet of the quite high "price" which must be paid when interferometers are used instead of parabolic reflectors. There are also two other interesting methods of raising the angular resolution, one utilizing the moon and the other utilizing the "solar wind."

When any radio source is "occulted" by the moon (that is, when the lunar disk comes between the source and a terrestrial observer), diffraction of the radio waves occurs at the limbs of the lunar disk. Because of the diffraction, reception of the radiation, even from a point source, does not stop immediately when the source disappears, but rather is found to vary gradually: the flux variation for occultation of a point source should follow the curve in Figure 10a. However, if the source is not a point source, the decay curve has a different shape. For example, for the well-known quasistellar source, quasar 3C 273 - B (these remarkable objects will be discussed below), the radio flux varies as shown in Figure 10b. By this mean angular resolutions of 1" or even higher can be attained. Unfortunately, the use of the method of lunar occultations is very restricted. First, many sources are never occulted by the moon, and, second, even when occultation can occur it may be only very rarely (sometimes many years go by between occultations).*

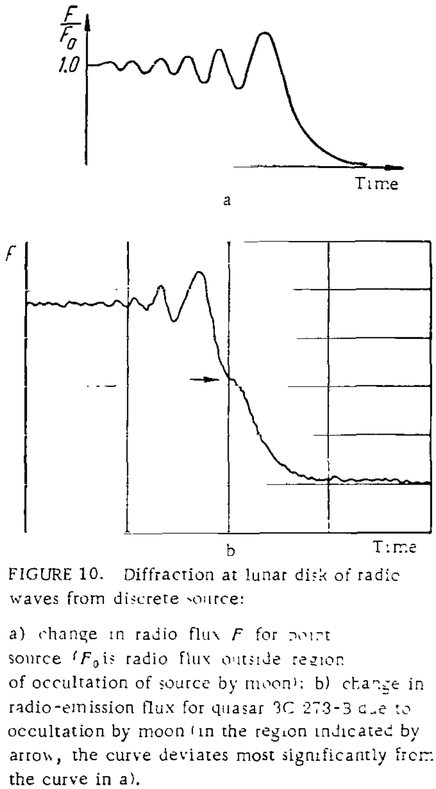


FIGURE 10. Diffraction at lunar disk of radio waves from discrete source:

a) change in radio flux $F$ for point source ($F_0$ is radio flux outside region of occultation of source by moon); b) change in radio-emission flux for quasar 3C 273-B due to occultation by moon (in the region indicated by arrow, the curve deviates most significantly from the curve in a).

In addition to the diffraction at the lunar disk, on its way to the earth the cosmic radio emission is also diffracted (albeit in a different way) by currents of the "solar wind." The solar wind consists of streams, jets, and "clouds" of ionized gas ejected by the sun. The sizes of the nonuniformities ("clouds") of the solar wind, and their distances from the earth, are such that a diffraction pattern is recorded on the earth (in the form of quite rapid oscillations of the radio flux from the source) only for sources with small angular dimensions. Consequently, the angular dimensions of a source can be evaluated and, what is more important, small sources can be

* Here we are referring to observations on the earth. It is always possible, in principle, to send a rocket to a point from which lunar occultation of any source occurs.

distinguished from large ones. In the middle of 1965 this method led to the discovery of a "compact" radio source in the Crab Nebula (the size of this source was 0.1", whereas the Crab Nebula itself has a size of 5' = 300" in the radio range, or 3000 times the size of the source).

The advances which nave been made during the development of radio telescopes, and in general in the reception and analysis of cosmic radio emission, have led to a number of results which are of interest in astronomy.

## COSMIC RAYS IN THE UNIVERSE AS A WHOLE (SUPERNOVA SHELLS, THE GALAXY, RADIO GALAXIES, QUASARS)

We have become accustomed to maps of the sky and photographs of different regions of the Milky Way or nebulae, obtained using optical telescopes. All these maps and photographs together show the distribution throughout the universe of the brightest luminous stars, star clusters, intragalactic nebulae, and galaxies. However, even in the visible range, a sky chart looks different when different light filters are used during the photograph (that is, in different wavelength ranges). As an example, Figure 11 shows photographs of the famous Crab Nebula (constellation Taurus), taken in the light of one of its intense spectral lines and in the light of the continuous spectrum (in this case a light filter which did not transmit the intense lines was used).

If the photographs are taken in infrared or ultraviolet light instead of visible light, the picture of the sky will naturally be changed even more than for the transition from red to violet light. However, in the radio range, the sky turns out to be completely unrecognizable. Although we do not possess "radio vision," in the literal sense of the word, it is still possible to view the sky in radio-frequency radiation on the screen of an oscilloscope. In practice, however, radio maps of the sky are constructed or simply drawn according to the data of measurements of the radio-emission intensity in different directions.

In the "optical sky" the sun occupies an exceptional position, and even the moon emits only one millionth as much light. However, in the meter range the "radio sky" has as many as three suns (three especially bright sources). One of these is the sun itself, another is the radio source Cassiopeia A, and the third is the source Cygnus A.* It is interesting that the two latter very powerful discrete sources of cosmic radio emission are quite insignificant in ordinary photographs, even when taken through a good telescope. Only on special photographs taken through the largest existing telescope (diameter 5 m) was it possible, in 1951, to detect reliably the shell of a supernova at the site of Cassiopeia A and a distant galaxy at the site of Cygnus A.

The Crab Nebula (radio source Taurus A) is one of the weaker radio sources: its radio flux at 3 m is only 1/12 of that of Cassiopeia A and 1/7 of that of Cygnus A.

* The difference between these sources when observed in the radio range is noteworthy. For instance, the angular size of the sun in the meter range is 40' to 50', whereas sources Cassiopeia A and Cygnus A are only a few angular minutes in size. In addition, the position of the sun in the sky changes due to the annual motion of the earth. Finally, the intensity of the solar radio emission in the meter range sometimes varies greatly when spots, flares, etc., appear on the sun.

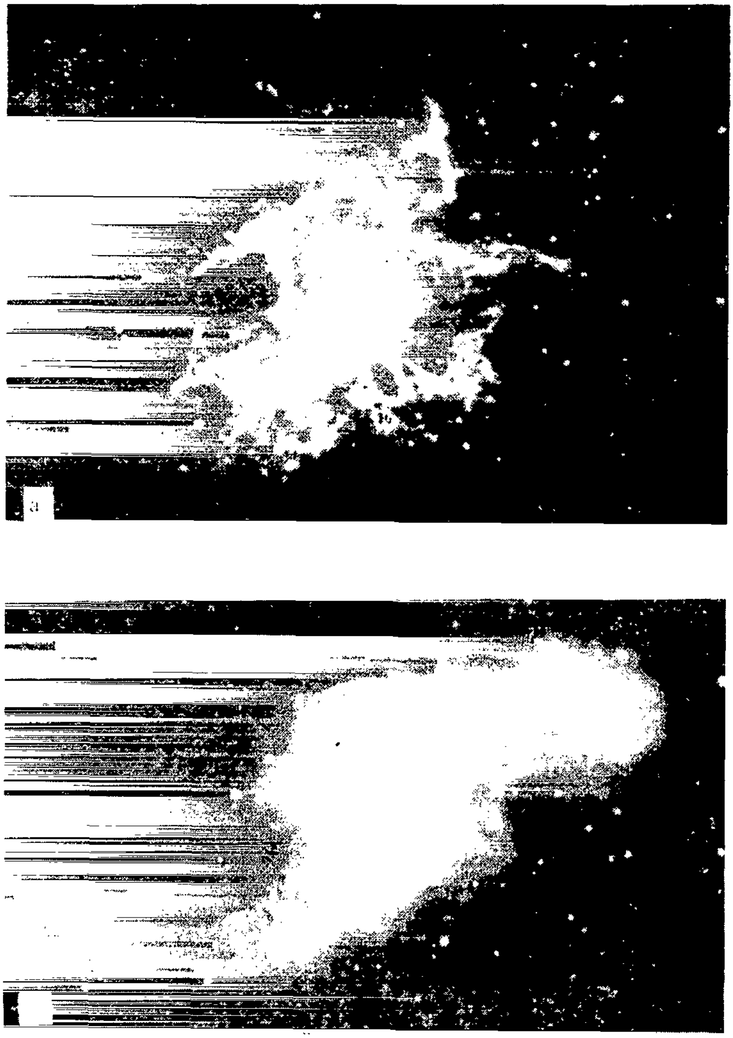

FIGURE 11. Crab Nebula (radio source Taurus A):

a) photograph taken in light of intense spectral line; b) photograph taken in light of continuous spectrum.

The difference between optical and radio maps of the sky becomes even more evident if we note that radio emission has never been detected from any bright star.* Finally, in addition to the presence of powerful discrete sources in the "radio sky," the entire sky is found to "shine" brightly in the meter range and at longer wavelengths. This is where the term "discrete

* Several years ago brief bursts of radio emission were seen to be emitted by certain variable (flaring) stars. Here, however, we are referring to radio-frequency radiation that can be observed at all times.

sources" of cosmic radio emission comes from, as opposed to sources which are continuously distributed in all directions. It was mentioned above that at 16 m the effective temperature of the continuous or, as it is more frequently called, general radio emission of the Galaxy is around $10^5$ °K. *

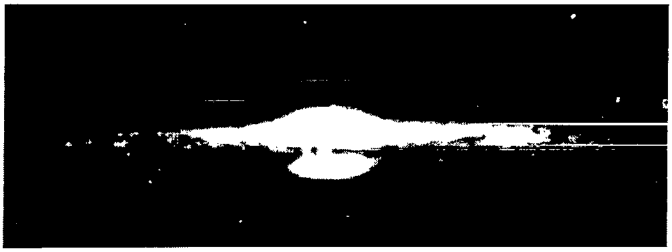

FIGURE 12. Galaxy NGC 4565 (here, NGC stands for New General Catalog, while 4565 is the number of the object in this catalog). The dark lane in the middle of the disk is caused by the absorption of light by cosmic dust concentrated in the galactic plane.

Let us determine the shape of the Galaxy when viewed in the radio-frequency range. First of all, however, it will be of interest to recall how the Galaxy looks in visible light. Naturally, it is not possible to photograph the entire Galaxy from somewhere inside it. Therefore, let us consider the photographs (Figures 12 and 13) of two spiral galaxies, one of which is seen from the earth in a "side view" and the other in a "top view." Our Galaxy, which is also a spiral galaxy, contains hundreds of billions of stars, the brightest of which form a bulge in the center of the disk. Spiral galaxies rotate quite rapidly. For example, the sun, which lies 30,000 light years away from the galactic center, makes one revolution around this center in about 220 million years; the velocity of the solar system associated with this motion about the center is about 230 km/sec. The arms of the galactic spiral, in which new stars and interstellar gas are concentrated, are by no means either regular or continuous. This is especially evident from data on the distribution of neutral hydrogen in the Galaxy, obtained from studies of the 21-cm radiation. The picture shown in Figure 14 was obtained on the basis of some of these data. Accumulations of hydrogen in the arms are represented as light bands, the galactic center is indicated by a cross, and

* According to (5), $T_{eff} = c^2 I_\nu / 2k\nu^2$, and for magnetic radio bremsstrahlung $I_\nu$ is usually proportional to $\nu^{-\alpha}$, where $\alpha = \frac{\gamma - 1}{2}$ (see 12)). For the general galactic radio emission, $\alpha \sim 0.6$ to 0.7, so that $T_{eff}$ is proportional to $\nu^{-2.6}$ or $\nu^{-2.7}$ Such a rapid drop in $T_{eff}$ with a rise in frequency indicates, for one thing, that the radiation is nonthermal. On the other hand, it is now clear why the total energy of the cosmic radio emission reaching the earth is comparatively low. Obviously, life of the earth would be impossible even if the radiation temperature (constant right up to infrared frequencies) were $T_{eff} \approx 400$°K. In the middle of 1965, data were obtained (and subsequently verified) indicating that thermal cosmic infrared and radio radiation exists which has a temperature of about 3°K.

the solar system by a circle with a dot in it. The region near the line between the sun and the galactic center cannot be studied in detail, so that the hydrogen accumulations there are far from being indicated completely. From Figure 14 and from a more detailed analysis, it is clear that the spiral arms are not continuous, but rather consist of separate parts which have different lengths and thicknesses.* These arms, finally, form only at a distance of about 9000 light years from the galactic center.

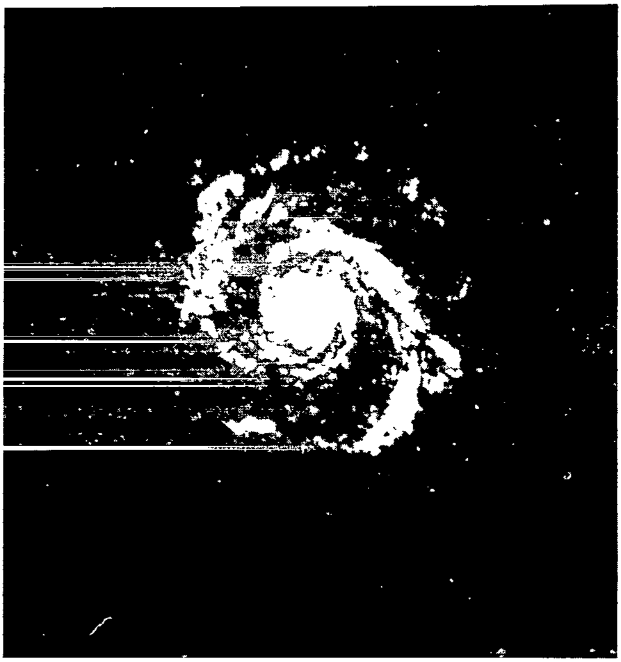

FIGURE 13. Galaxy NGC 5194.

A detailed study of the spiral structure and the central regions of the Galaxy using optical methods is impossible, due to the interstellar absorption of light. However, with the development of radio astronomy, important results were immediately obtained in this direction. In particular, a galactic nucleus about 20 light years across was discovered. This nucleus is a

* A quasiordered magnetic field ($H \sim 10^{-5}$ oersted), oriented predominantly along the arm, exists in the spiral arms of the Galaxy. The arms seem to form force tubes of the magnetic-field lines, and the magnetic field undoubtedly plays an important part in the creation of the arms. The fact that the arms do not form any kind of regular spiral is explained by the rotation of the Galaxy. During the time the Galaxy has existed in a state close to the present one (about 9 billion years), for example, the solar system has completed about 25 revolutions around the galactic center. Obviously, the force tubes could not have remained unbroken during that time. Here it is important to note that the Galaxy (and, in general, galaxies) does not turn as a solid body; on the contrary, its rotation is nonuniform (this means that the angular velocity of rotation varies with the distance from the rotation axis).

source of nonthermal radio emission, and in addition it may be a small quasar (see below). The area surrounding the nucleus has turned out to be equally interesting; it is a layer of neutral hydrogen with a thickness of about 300 light years. Here, $n \sim 1$ to $2\ \mathrm{cm}^{-3}$, and the entire mass of hydrogen revolves rapidly around the galactic nucleus (more precisely, around some center that apparently coincides with the center of the nucleus). The central part of the Galaxy is also a source of more intense nonthermal radio emission, in comparison with the adjacent regions. This can probably be attributed to an enhancement of the magnetic field in this region, rather than to an increase in the number of cosmic rays. For example, for $\gamma = 2.4$, formula (11) shows that the radio-emission intensity is proportional to $H^{1.7}$.

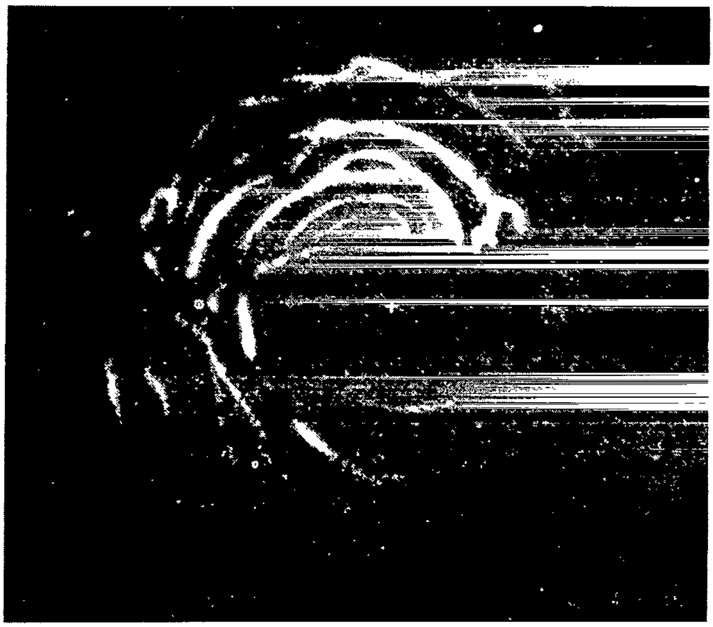

FIGURE 14. Accumulations of neutral hydrogen in Galaxy.

Actually, we have already changed to a description of the sky according to the radio emission in the meter range. Two elements of this description are the above-mentioned galactic nucleus (a source of thermal radio emission) and the central radio region, which is a source of radio-frequency magnetic bremsstrahlung of increased intensity. Roughly speaking, this source has the shape of an ellipsoid of revolution, with axes $\sim 1000$ and 400 light years long (Figure 15). The third element of the description is the radio disk of the Galaxy, a region $\sim 1500$ light years in thickness.* The radio disk encompasses the optical disk of the Galaxy with its spiral structure (the arms of the optical spiral are $\sim$ 800 light years in thickness). Finally, the last element of the radio picture of the Galaxy is the halo, or corona, a nearly spherical region which encompasses the entire visible

* More recent data show this thickness to be 2500 light years.

Galaxy. From 80 to 90% of the total galactic radio emission comes from this region, which has a radius of 30,000 to 50,000 light years.* Apparently there is no clear-cut boundary between the radio disk and the halo; it is just that there is an increase in the radio brightness of the halo closer to the galactic plane. Figure 16 shows two curves for the effective temperature of the cosmic radio emission at 3.5 m, as a function of the galactic latitude (let us recall that the galactic latitude is reckoned from the galactic plane, which corresponds to a latitude of 0°; the galactic longitude determines the position of the line of sight in the galactic plane). The curves correspond to different galactic longitudes. Measurements made using high-resolution instruments indicate that the radio disk is nonuniform, in that its radio brightness varies quite strongly from point to point (that is, the radio disk apparently has a "patchy" structure).

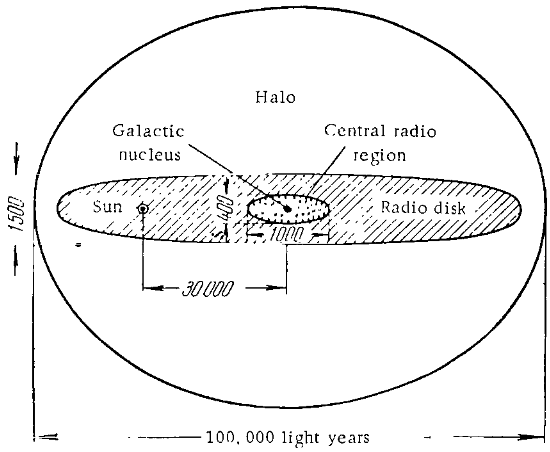


FIGURE 15. Schematic representation of Galaxy from meter-range radio emission.

Therefore, in the radio range the Galaxy is by no means comparable to a thin disk with a bulge in the middle. On the contrary, it has the shape of a sphere or a slightly oblate ellipsoid. The same can be said, and with even greater certainty, about most other galaxies, in particular about the Great Nebula in Andromeda, which is the spiral galaxy closest to us. It is true that there are some galaxies which do not have bright radio halos. Nevertheless, the fact that at least some galaxies were shown by radio observations to possess halos represents one of the important achievements of astronomy in recent times. This fact is especially relevant to the present discussion, since the radio emission of the halo is caused by the presence in these gigantic galactic shells of relativistic electrons and cosmic rays in general, as well as magnetic fields. In addition, highly rarefied ionized gas

* The exact shape of the galactic halo is still unknown. It may be that only around 50% of the galactic radio emission comes from the halo.

is present in the halo (mean concentration $n \sim 1 \cdot 10^{-3}$ to $3 \cdot 10^{-3}$ cm$^{-3}$), and the magnetic fields are "frozen into" this gas. The very existence of the halo is apparently closely related to cosmic rays. Cosmic rays produced in the central radio region and in the radio disk leave these parts of the galaxy, carrying magnetic fields and gas along with them. The cosmic rays are quite securely "attached" to the lines of force of the field, and the field itself is carried away by the gas, through which the currents produced by the field flow. Finally, this interrelation between cosmic rays, field, and gas motion can be close and mutual only if the energies of all these "inhabitants" of interstellar space are comparable. And this is actually the case!

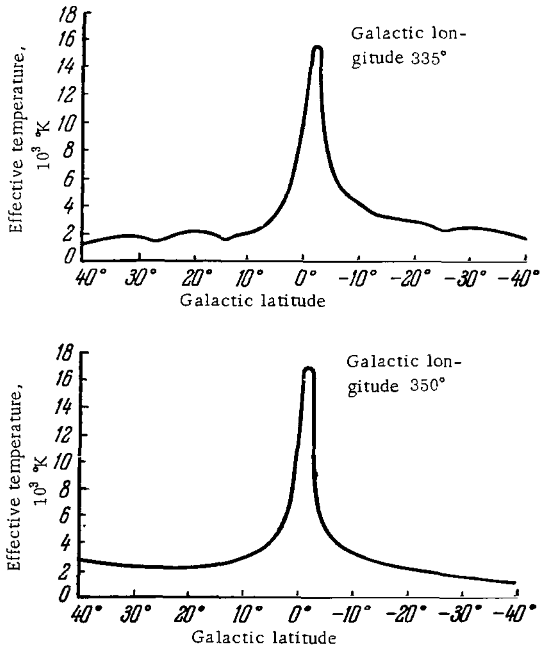


FIGURE 16. Effective temperature of 3.5-m galactic radio emission.

The concentration of cosmic rays near the earth is $N = \frac{4\pi}{c} I \sim 10^{-10}$ cm$^{-3}$, and the mean energy density is $w_{\text{c.r.}} = N\bar{E} \sim 1$ ev/cm$^3$ (the average particle energy is $\bar{E} \sim 10^{10}$ ev, where 1 ev $= 1.6 \cdot 10^{-12}$ erg). In the halo the energy density $w_{\text{c.r.}}$ is probably, on the average, only a few times less than this, say, 0.3 ev/cm$^3$. At the same time, the energy density of the magnetic field $H^2/8\pi \sim 0.3$ ev/cm$^2$ for a field with $H \sim 4 \cdot 10^{-6}$ oersted. However, such fields also exist in the Galaxy (in the spiral, it is probably true that $H \sim 10^{-5}$ oersted, while at the periphery of the halo $H \sim 1 \cdot 10^{-6}$ to $3 \cdot 10^{-6}$ oersted). Finally, the mean density of the interstellar gas for a mean concentration $n \sim 10^{-2}$ cm$^{-3}$ is of the order of $\rho \sim 2 \cdot 10^{-26}$ g/cm$^3$ (this gas is 90% hydrogen, and the mass of the hydrogen atom is $1.67 \cdot 10^{-24}$ g). Thus the kinetic-energy density of the gas $\rho v^2/2$ is of the order of 0.3 ev/cm$^3$ for a velocity $v \sim$ $\sim 7 \cdot 10^6$ cm/sec. The observed velocities of random motion of the gas masses in the Galaxy are usually several times less than this, but then the density in observed gas clouds is considerably higher than that assumed. In general, the mean kinetic-energy density of the gas $\rho v^2/2 \lesssim w_{c.r.}$.

From the foregoing it is evident that the cosmic rays in our Galaxy are not a side product or secondary phenomenon. On the contrary, the effect of the cosmic rays is one of the factors determining the "energetics" of the structure and evolution of the entire system. The same is true for most other galaxies as well. This is evident from the fact that the energies of the cosmic-ray radio emission in our Galaxy and in the galaxy in Andromeda are of the same order (about $1 \cdot 10^{38}$ to $3 \cdot 10^{38}$ ergs/sec). The two irregular galaxies closest to us, the Magellanic Clouds, emit only $^1/_{10}$ as much, but the dimensions of these galaxies are also comparatively small. All this implies that cosmic rays perform almost the same function in "normal" galaxies as they do in our stellar system. However, although this function is important, the energy of the radio-frequency radiation of a normal galaxy is only a small fraction of the total energy emitted, which is concentrated primarily in the visible and infrared parts of the spectrum. For example, the emission (luminosity) of the Galaxy is $\sim 10^{44}$ ergs/sec, which amounts to $3 \cdot 10^{10}$ times the energy emitted by the sun ($3.86 \cdot 10^{33}$ ergs/sec) and $10^6$ times the energy emitted by the Galaxy in the radio range.

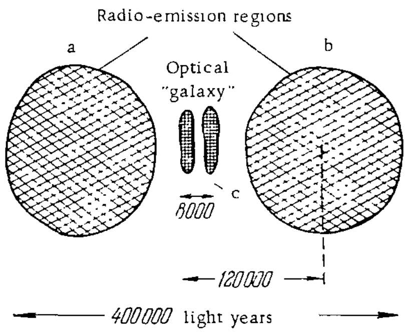


FIGURE 17. Schematic representation of source Cygnus A.
Out of scale; dimensions, in light years, are tentative.

There are, however, some anomalous galaxies, also known as radio galaxies, which emit an exceptionally large amount of energy in the radio range. One of the most interesting and most familiar of these is radio source Cygnus A. This source emits about $5 \cdot 10^{44}$ ergs/sec in the radio range, or nearly $10^7$ times that of our Galaxy. This, of course, is the reason why Cygnus A, which is 600 million light years away, has a radio "brightness" comparable to that of the sun. Remarkably enough, in the optical range the emission of Cygnus A is about $10^{44}$ ergs/sec, which is only about $^1/_5$ of the radio emission.

What sort of object, then, is this unusual source? Comparatively recently, it was still widely believed that Cygnus A actually constitutes two colliding galaxies. There was some basis for this point of view, since the source in question is a double source (Figure 17). Now, however, it is considered certain that this is not a case of colliding galaxies, but rather of an unusual "explosion" of a galaxy. Such an "explosion" of a galaxy is (if we exclude the expansion of the entire Metagalaxy, the whole observable system of galaxies) the most grandiose and mighty phenomenon in nature. The cause of this "explosion" of the galaxy in Cygnus has not yet been established reliably, but apparently the course of events was approximately as follows. Several million years ago, or perhaps only one million years ago, an intensive production of cosmic rays began in a hitherto relatively quiet galaxy, or in an enormous gas cloud from which a stellar galaxy then formed. A possible cause of this process will be discussed at the end of the book. The ever-increasing cosmic-ray pressure resulted in the following: rapid particles, together with the magnetic fields and interstellar gas associated with them, were thrown outward. This "outburst" evidently took place along the rotation axis of the galaxy in both directions, and it led to the formation of "clouds" a and b in Figure 17. It is from these "clouds," which are larger than our entire Galaxy, that the radio emission of Cygnus A comes. The stellar galaxy itself is located between the "clouds." Either it is now a binary system or else it contains so much dust that there is a dark obscured area in the middle (in Figure 17 the luminous regions are cross-hatched and the dark area corresponds to region c).

Let us assume that the energy densities of the magnetic field and the cosmic rays are of the same order, and also that the electron (and positron) content of the cosmic rays is about 1%. Then it is possible to evaluate the total energy of the cosmic rays in the source. For Cygnus A we obtain $W_{c.r.} \sim \sim 3 \cdot 10^{60}$ ergs (for our Galaxy, as will be seen below, $W_{c.r.} \sim 10^{56}$ ergs). In order to emphasize the immensity of this number, we note that the total potential energy of the sun is $M_{\odot}c^2 = 1.8 \cdot 10^{54}$ ergs, since the mass of the sun is $M_{\odot} = 2 \cdot 10^{33}$ g. The potential energy of the whole Galaxy (mass around $10^{11} M_{\odot}$) is of the order of $2 \cdot 10^{65}$ ergs.

The electrons lose energy as they emit radio waves, so that the brightness of the source should diminish with time. If there were no "replenishment" of the cosmic-ray energy in Cygnus A, the radio emission would diminish considerably during the course of a million years.* In other words, sources like Cygnus A remain extremely bright for a comparatively short time. As time goes by, not only should the source brightness diminish, but also the source should grow larger, because the radio-emitting "clouds" of gas and cosmic rays expand and become further apart. Consequently, there are very few sources like Cygnus A, and at distances comparable to its distance from our Galaxy there is not even one other source with a comparable brightness, although millions of galaxies exist in this region.** However, there are also some sources which are somewhat similar, but older and weaker, that lie even closer than Cygnus A. One of these is Centaurus A (galaxy NGC 5128), which has a structure similar to that shown in Figure 17 except that the clouds and the distances between clouds are much bigger (in addition, the central, "optical" regions of Cygnus A and Centaurus A also differ greatly. Sources even older than this are probably unobservable, since the radio-emitting "clouds" have become very large and dark. However, the central part of a radio galaxy may differ but little from that of a normal galaxy (although it has been established that practically all radio galaxies are optically bright elliptical galaxies). If radio galaxies are sin-

* The energy of the electrons in Cygnus A is assumed to be $0.01\ W_{c.r.} \sim 3 \cdot 10^{58}$ ergs, and this source emits $5 \cdot 10^{44}$ ergs/sec. Thus it is clear that the emission energy varies substantially during a time of the order of $5 \cdot 10^{13}$ sec $\sim 2 \cdot 10^{6}$ years. Such a time period, which is colossal in comparison with a human lifetime, is very short compared to the billions of years it took for most large galaxies to evolve. A "replenishment" of the energy as a result of the production of new cosmic rays lengthens the duration of the intensive radio emission of Cygnus A. However, this can hardly vary the characteristic lifetime of the source by more than one order of magnitude.

** A galaxy requires, on the average, a volume of $5 \cdot 10^{6}$ cubic light years $\sim 10^{74}$ cm$^3$. The furthest galaxies whose distances can be evaluated are 5 to 8 billion light years away. Interestingly enough, these sources were also discovered in the radio range.

gled out for their high brightness "at present," then one radio galaxy corresponds to approximately several thousand normal galaxies. *

It should not be thought, however, that all radio galaxies are like Cygnus A when viewed in the radio range. On the contrary, they can have a great variety of shapes, and in addition each galaxy may have its own special features. As an example of a radio galaxy which is quite different from Cygnus A, let us cite Virgo A (galaxy NGC 4486). This bright galaxy is not divided into two parts and it has the following very interesting "detail": a brightly luminous "ejection" (Figure 18), when viewed in the visible range. The optical radiation of this "ejection" has a continuous spectrum and, what is most important, is highly polarized. These two things, especially the presence of polarization, leave no doubt whatsoever but that this is a case of magnetic bremsstrahlung in the optical part of the spectrum. The Crab Nebula, which is the shell of a supernova, is another well-known example of a radio source in which there is optical magnetic bremsstrahlung (more precisely, here the part of the Crab Nebula's radiation which has a continuous spectrum is referred to; therefore, the photograph in Figure 11b was taken essentially in the range of magnetic bremsstrahlung).

Optical magnetic bremsstrahlung is apparently observed in nebulae due to the presence in them of an appreciable number of high-energy electrons. ** The optical magnetic bremsstrahlung of the Crab Nebula and of the "ejection" in Virgo A are polarized. This is because the depolarizing effect of the interstellar medium is negligible at high frequencies and also because it is possible to photograph small parts of nebulae. The degree of polarization of the optical radiation of the entire Crab Nebula amounts to 9%, whereas in individual small regions the polarization is almost complete. In the centimeter range the polarization of the Crab Nebula is still appreciable (at 10 cm it is about 3%, but at 20 cm it is already less than 1%).

The Crab Nebula (its other name is Taurus A) lies within the Galaxy, about 4500 light years away from us. This nebula was produced in 1054 A.D., as a result of a supernova explosion. Due to a fortunate combination of circumstances, this star was located comparatively nearby and also in a direction in which the sky was relatively "clear" (that is, in which there was only a small amount of cosmic dust). The supernova outburst of 1054 was so bright that it was easily observable in the daytime (we should note that even Venus, the brightest of all the stars and planets, is rarely visible by day). Naturally, such an event did not go unnoticed, and the appearance of a new star † in constellation Taurus was recorded in the Chinese and

* In order to avoid misunderstandings, let us recall that in astronomy time is reckoned from the moment of observation on the earth. Consequently, when we say that a source like Cygnus A is now bright, this actually means that it was bright 600 million years ago, since this is the time it took for the light to reach us from this source.

** Using formula (8) it is easy to show the following: for a field of, say, $H_{\perp} \sim 3 \cdot 10^{-4}$ oersted and electrons with energies $E \sim 5 \cdot 10^{11}$ ev, the peak of the magnetic-bremsstrahlung spectrum corresponds to $\lambda = c/\nu_{max} \sim$ $\sim 0.7$ micron, that is, it lies in the visible part of the spectrum. In laboratory experiments (in synchrotrons), in a field of $H \sim 5000$ oersteds, the same emission spectrum is obtained for electrons with $E \sim 100$ Mev = $= 10^8$ ev. Magnetic bremsstrahlung can be observed in synchrotrons without any special difficulty.

† In the more narrow, or special, sense of the word, "new star" or "nova" is used to mean a star which flares up so that its brightness is thousands of times less than the star in Tauras at the time of its outburst. Accordingly, this star and similar objects are termed, somewhat inappropriately, "supernova stars" or "supernovae." Around 100 novae flare up in the Galaxy per year, but because of interstellar light absorption only a couple of these can be seen.

Japanese chronicles of that time. The Crab Nebula is observed in that very same place today.

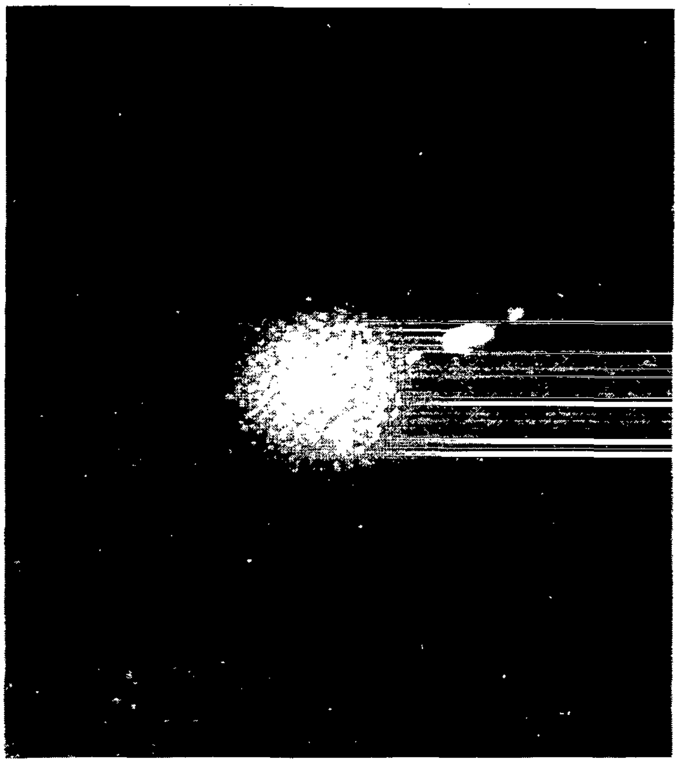

FIGURE 18. Photograph of brightest (central) part of radio galaxy NGC 4486 (radio source Virgo A).

A supernova outburst is the most powerful phenomenon taking place in the galaxies, except for the explosion of a galactic nucleus (see below). For some days or a week after the outburst, the brightness of the optical radiation of a supernova is comparable to the brightness of the entire galaxy in which the flareup occurred. This means that the emission intensity of a supernova at peak brightness may be many billions of times greater than the emission intensity of the sun.

The frequency of supernova outbursts in the Galaxy has not been established accurately. Apparently, a supernova flares up, on the average, once every 50 to 100 years. The difficulty in determining the outburst frequency is related to the interstellar light absorption, which hinders the observation of supernovae in the Galaxy; another limiting factor is the relative infrequency of the outbursts. Supernova outbursts in other galaxies are observed more easily. The outburst frequency depends on the type of galaxy; for spiral galaxies there are apparently supernovae once in a hundred or several hundred years.

The nature of the outbursts has not yet been explained. One possible reason is that a rapid compression of the central region may take place in certain especially massive young stars during the course of their evolution; this compression may be accompanied by the formation of a neutron nucleus. (Stellar evolution is associated with thermonuclear reactions in the interiors of stars. Sudden variations in the course of these reactions cause certain elements to "burn up.") The gravitational energy released during compression results in an explosion and a dispersion of the entire outer part of the star. The expanding shells of supernovae are probably also formed in this way. The shell of the Crab Nebula moves with a velocity of about 1000 km/sec. For comparison, we recall that the velocity of a close artificial satellite is 8 km/hr. For more than 900 years (since the time of the explosion), the fragments of the shell have moved outward over a distance of 3 light years, which is the present radius of the Crab Nebula. It is noteworthy that the "young" shells of supernovae are powerful sources of nonthermal cosmic radio emission. The Crab Nebula has already been discussed. Other "historical" supernovae also emit radio waves, although of somewhat lower intensity: Tycho Brahe's supernova (1572), Kepler's supernova (1604), and some others. Finally, it has been established that the most powerful source of nonthermal radio emission in the sky, Cassiopeia A, is the shell of a supernova which flared up about 250 years ago. The optical effect of the outburst of this supernova was not observed, due to interstellar light absorption (Cassiopeia A if of the order of 10,000 light years away). The velocity of dispersion of the shell of this supernova is more than 7000 km/sec!

The intense radio emission of the shell of a supernova is undoubtedly connected with the presence in the shell of a large number of relativistic electrons. There is also considerable evidence that a great many other high-energy particles (cosmic-ray particles) are present in the shells.

In the last 3 or 4 years some important discoveries have been made which have a close bearing on the material being discussed here. First, the x-ray emission from the Crab Nebula, and from several other objects whose natures are as yet unclear, was discovered. This will be discussed in more detail in the next chapter.

Second, as already noted, a "compact" radio source was detected in the Crab Nebula. The smaller source radiates at 8 to 12 m and is only a few times weaker than the entire nebula. This compact source is only about $10^{-3}$ light year in size ($\sim 10^{15}$ cm). This is $^{1}/_{3000}$ of the size of the nebula itself in the radio range and in order of magnitude it corresponds to the dimensions of the solar system. The nature and structure of the compact source in the Crab Nebula are unknown, but most likely this source is associated with the debris of the supernova. It may be, for example, a star with a neutron core, surrounded by an intense magnetosphere (which possesses a large magnetic moment) and by an extended gaseous envelope ("corona").

Third, an even more impressive discovery was made a few years ago (1963), namely the discovery of quasistellar sources, or quasars (also sometimes called superstars). The radio sources listed in the 3rd Cambridge Catalog (these sources are designated by the code 3C with an appropriate number after it) include several objects whose locations almost coincide with those of optical sources which are indistinguishable on the photographs from ordinary stars. In addition, these radio sources have anomalously small angular dimensions. Consequently, for some time it was thought that a new type of star had been discovered, a star which was very bright in the radio range ("radio star"). However, these sources actually turned out to be quasars, which are starlike radio sources located far beyond the limits of the Galaxy and which are objects of an entirely new type. These objects (quasars) have optically bright cores (nuclei) which are comparatively small, from 0.01 to several light years in size. And the amazing thing is that this "nucleus," which has a diameter many thousands of times less than that of our Galaxy, sometimes emits tens of times as much light as the entire Galaxy! For example, the very bright quasar designated as source 3C 273-B emits 100 times as much light as our Galaxy in the visible part of the spectrum alone. Thus quasar 3C 273-B, which is about $1^1/_2$ billion light years away, shows up as a quite bright star on photographic plates. The situation is similar for quasar 3C 48, which is twice as far away (Figure 19). Only by spectral analysis is it possible to differentiate between quasars and stars and to determine the distance to a quasar. *

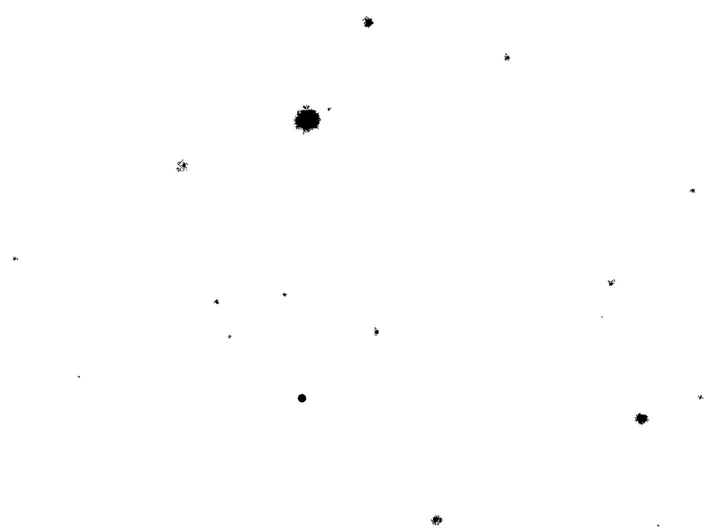

FIGURE 19. Photograph (negative) taken through 200-in. telescope. Quasar 3C 48 indicated by white arrow.

* The entire observable universe (or, as it is called, the Metagalaxy) is expanding, that is, the distances between remote galaxies are continually increasing. The greater the distance between galaxies (in particular, between our Galaxy and any other one), the greater will be the velocity of their separation. The wavelength of the radiation emitted by a receding object is known to increase, to shift toward the red (Doppler effect). Consequently, the further away a galaxy is from us, the greater will be the red shift of its spectral lines (also known as the cosmological red shift). Thus red-shift measurements indicate the distance to a galaxy or quasar. For quasars 3C 273-B and 3C 48, the relative wavelength variations $\frac{\lambda - \lambda_0}{\lambda_0}$ are, respectively, 0.16 and 0.37. For one of the remotest quasars known today, quasar 3C 9, this ratio is $\frac{\lambda - \lambda_0}{\lambda_0} = 2$ (!).

So far it has not been determined whether a quasar is the nucleus of some existing stellar system (galaxy) which is not visible on photographs, or whether it has no connection with any galaxy and is simply a gigantic variable star (superstar) formed from the intergalactic gas. In any case, there is probably some relation between quasars and exploding galactic nuclei (such explosions are typical and they lead to the formation of radio galaxies). Incidentally, in 1963 astronomy was enriched by a photograph of an explosion in one of the comparatively weak, but at the same time nearby, radio galaxies, galaxy M 82 (where M stands for Messier's catalog). This photograph (Figure 20) shows masses of hydrogen moving out from the central part of the galaxy (the explosion occurred about $1^1/_2$ million years ago). Just as in the case of Virgo A and the Crab Nebula, part of the visible radiation of galaxy M 82 is polarized and doubtless is associated with magnetic bremsstrahlung. In all probability, the same applies to most of the optical and radio emission of quasars. As we have already mentioned, the nucleus of our Galaxy may also be a small quasar which emits magnetic bremsstrahlung. However, in the place where the magnetic bremsstrahlung is produced, there are relativistic electrons and, most likely, heavier particles (that is, cosmic rays) as well.

FIGURE 20. Explosion in radio galaxy M 82. Photograph taken through 200-in. telescope.

To sum up, cosmic rays are found in the Galaxy and in other "normal" galaxies; they are especially numerous in radio galaxies, and they are produced in great quantities during supernova outbursts and explosions of galactic nuclei. Cosmic rays (or, more precisely, their electron component) are responsible for a considerable portion of the cosmic radio emission. Thus, radio astronomy has added immensely to our information on cosmic rays, and it has shown that they essentially pervade the entire universe.

*Chapter 3*

## *GAMMA-RAY AND X-RAY ASTRONOMY*

For a long time cosmic rays far away from the earth (and outside the range of rockets) could be studied only according to their radio-frequency and (to a lesser degree) optical magnetic bremsstrahlung. Now, however, the situation is different, since quite definite cosmic-ray information can also be obtained using the techniques of gamma-ray and x-ray astronomy.

Whereas radio astronomy extended the useful spectrum of electromagnetic waves toward longer wavelengths (from millimeters to hundreds of meters), gamma-ray and x-ray astronomy widen this spectrum on the short-wave side (wavelengths less than a few Ångströms).* Thus the range of useful waves became incomparably wider than the narrow "optical transmission window" in the earth's atmosphere, which throughout the entire preceding period had set a limit to astronomical observations (Figure 21).

It will be advisable to discuss gamma-ray and x-ray astronomy at some length here. First, it should be noted that there is no clear-cut definite boundary between gamma ($\gamma$) rays and x-rays. Generally, the following two types of radiation are called x-radiation: the short-wave ($\lambda < 10$ to $100$ Å) radiation emitted by fairly heavy atoms, and the radiation produced during the deceleration of quite rapid, but still nonrelativistic, electrons. When such radiation is emitted by atomic nuclei, it is more commonly known as $\gamma$-radiation. Usually, though, $\gamma$-rays are harder (they have lower wavelengths) than x-rays. Let us take this (and only this) as our basic criterion and let us call, albeit somewhat arbitrarily, all photons with energies greater than 0.1 Mev$= 10^5$ ev (that is, with wavelengths shorter than 0.1 Å) $\gamma$ rays. Radiation with a wavelength higher than this (0.1 Å$< \lambda <$100 Å, 100 ev$< E_\Phi <$ $<10^5$ev) will be called x-radiation.

### Gamma-Ray Astronomy

Let us begin by listing the various processes which can produce $\gamma$-rays.

1) During certain transitions between levels in atomic nuclei, $\gamma$-rays with energies up to about 10 Mev are produced (Figure 22a).

* Let us recall that 1 Å (Ångström) $= 10^{-8}$ cm $= 10^{-4}$ $\mu$, and that the energy of light quanta (photons) is $E_\Phi = h\nu$, where $h$ is Planck's constant and $\nu$ is the radiation frequency. The wavelength $\lambda = 12{,}345/E_\Phi$, where $\lambda$ is in Å and $E_\Phi$ is in ev.

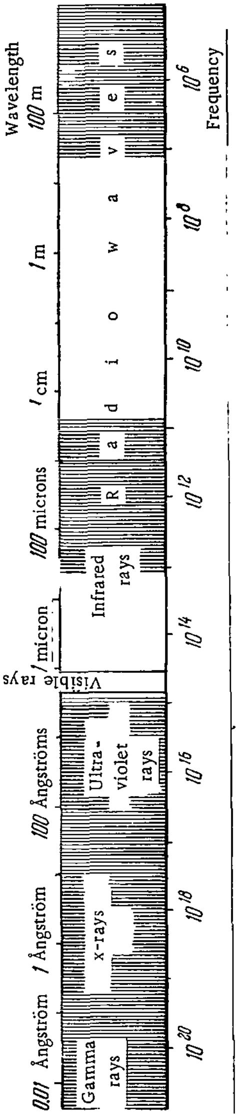


FIGURE 21. Scale of electromagnetic waves.

Light regions correspond to radiation for which atmosphere is transparent or, more precisely, radiation which is not so greatly absorbed that observation from earth's surface is hindered.

2) Gamma rays are generated during the annihilation of electron-positron pairs (Figure 22b). If the electron and positron have low velocities and the annihilation takes place in a vacuum, then usually only two $\gamma$-photons are produced. Each of these has an energy $mc^2 = 0.51$ Mev, where $m = 9.1 \cdot 10^{-28}$ g is the electronic mass.

3) Gamma rays also appear when electrons having velocities close to the velocity of light are decelerated, for instance, as a result of collisions with protons or stationary electrons. Then electromagnetic radiation equivalent to photons with energies $E_{\Phi} \lesssim E_e$ will be emitted (Figure 22c). Consequently, braking $\gamma$-rays are produced by electrons with energies $E_e > 0.1$ Mev.

4) Electrons with fairly high energies also generate $\gamma$-rays as a result of scattering on optical (light) photons (the so-called Compton effect).* In the latter process rapidly moving electrons impart some of their energy to light photons when they collide with them (Figure 22d). Thus the energy of the scattered photons is, on the average, $(E/mc^2)^2$ times greater than the photon energy before scattering. For example, photons with energies of about 1 ev produce $\gamma$-rays with energies $E_{\gamma} > 0.1$ Mev, when they are scattered on relativistic electrons (with energies $E > 300\ mc^2 \approx 150$ Mev) moving in a direction opposite to them.

5) Neutral ($\pi^0$) and charged ($\pi^{\pm}$) mesons are produced when cosmic rays collide with nuclei of the interstellar gas. The neutral mesons decay very rapidly, and two gamma-ray photons are generated (Figure 22e). The energy of these photons depends on the velocity of the $\pi^0$ meson prior to decay and on the direction of its motion, but it almost always exceeds 50 Mev.

Therefore, except for nuclear and annihilation $\gamma$-rays with comparatively low energies, the basic role in the generation of $\gamma$-radiation is played by fast particles, particularly cosmic rays (including the electron component).

* The scattering of $\gamma$-ray photons on stationary or slowly moving electrons is usually called the Compton effect. Accordingly, the scattering of high-energy electrons on optical photons (for solar radiation the average energy of these photons is about 1 ev) is sometimes known as the inverse Compton effect. In both cases, however, we are dealing with the very same phenomenon, so only the term "Compton effect" will be used here.

The intensity of the $\gamma$-rays produced in some part of the universe will obviously be proportional to both the intensity (flux) of the cosmic rays generating them and the concentration of gas (or of photons, in the case of process 4) in this region. Some information on the distribution of interstellar gas has already been obtained using the techniques of optical and radio astronomy. This, as well as the distribution of cosmic rays throughout the universe, was discussed earlier in the book.

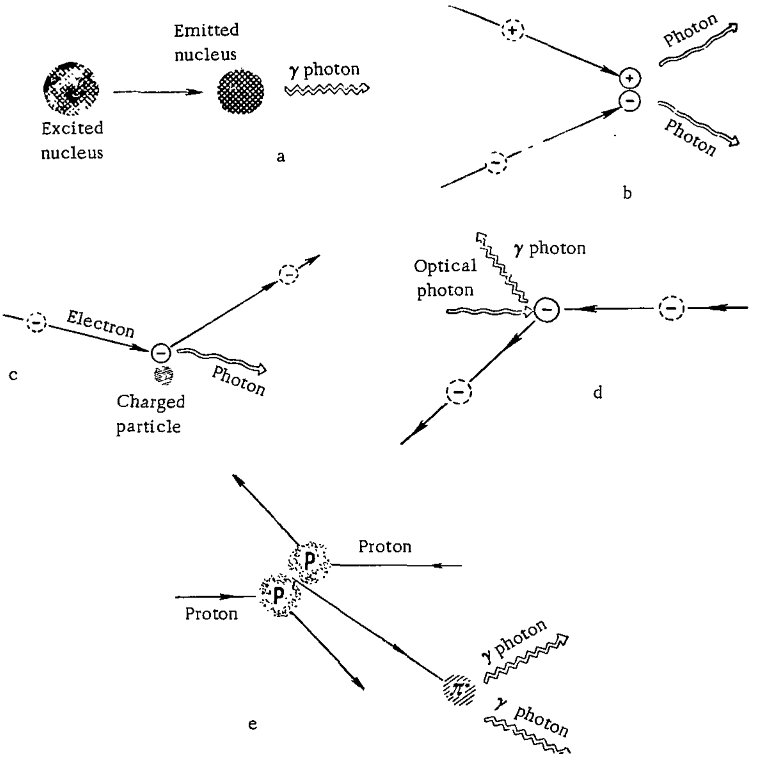


FIGURE 22. Processes in which gamma rays are generated:

a) radiation caused by excitation of atomic nucleus; b) annihilation of electron-positron pair; c) bremsstrahlung from collision of electron with nucleus; d) scattering of electrons on photons (Compton effect); e) creation and decay of $\pi^0$ mesons.

Unlike cosmic rays, but similarly to radio waves, $\gamma$-rays propagate through the universe in a rectilinear manner, almost without absorption. Therefore, $\gamma$-ray observations provide, in principle, a direct means of studying the lateral distribution of the cosmic rays producing the $\gamma$-rays. In addition, such observations may give more accurate data on the gas densities in interstellar and intergalactic space.

Of particular interest is the possibility of studying the Metagalaxy using gamma-ray astronomy. So far, very little has been learned about cosmic rays in the Metagalaxy (that is, outside of the Galaxy). However, the initial results of gamma-ray astronomy have already made it possible to draw some important conclusions concerning this subject.

The intensity of $\gamma$-rays with energies greater than 50 Mev was measured by the satellite Explorer XI. The upper limit of the gamma-radiation flux from space was found to be $\sim 10$ photons/$m^2$ sec.

These data show that the intensity of the electron component of cosmic rays in the Metagalaxy is considerably less than ($^1/_{30}$ of, and perhaps even $^1/_{100}$ of) the corresponding intensity in the Galaxy. Otherwise, as a result of Compton scattering on light photons emitted by stars and galaxies (process 4), the $\gamma$-ray flux would be higher than the upper limit established by the experiment (analogous conclusions will be drawn below with regard to x-rays).

The low intensity of the electron component makes it very probable that the total cosmic-ray intensity (protons and heavier nuclei included) in the Metagalaxy is also low. A definite verification of this conclusion will be possible when experiments on the observation of cosmic $\gamma$-rays are made more accurate, and in particular when the observed intensity of $\gamma$-rays from process 5 (production and decay of $\pi^0$ mesons in intergalactic space) is evaluated.

The metagalactic gamma radiation comes toward the earth uniformly from all directions. The gamma radiation of galactic origin, on the other hand, is nonisotropic. For example, the galactic $\gamma$-rays produced by $\pi^0$-meson decay (process 5) will, in the main, come from the direction corresponding to the center of the Galaxy, since most of the interstellar gas is concentrated in this direction.

In addition to the overall metagalactic and galactic gamma radiation generated in intergalactic and interstellar space, $\gamma$-rays emitted by individual sources (particularly quasars) are also of great interest. Most of the optical radiation of quasars is assumed to have a magnetic-bremsstrahlung origin. If this is indeed the case, then in the emission region (around the "nucleus" of the quasar) there will be a large number of relativistic electrons. However, there will also be a very high density of optical radiation in this region (high concentration of optical photons). This follows from the relatively small size of a quasar and from its gigantic optical luminosity (optical-emission intensity). As a result of this combination, a quasar should be an especially powerful source of Compton $\gamma$-rays, produced by scattering of optical photons on relativistic electrons (process 4).

In other words, quasars may turn out to be very powerful $\gamma$-ray sources, as well as outstanding sources of optical radiation. Unfortunately, as far as we know, no attempt has as yet been made to record the gamma radiation of quasars. Moreover, such measurements will be especially difficult if quasars turn out to be somewhat larger than thought, as a result of which the photon concentrations at their "surfaces" will be correspondingly less than those given by optimistic estimates. However, one thing is quite clear: the reception of gamma radiation from discrete sources is quite feasible, and such $\gamma$-ray measurements may well open up new horizons in astronomy.

In order that this possibility will not appear to be too problematic, we note that the gamma radiation from one "discrete" source can not only be received but is even actually measurable. Here we are referring, of course, to the sun. The importance of solar processes to life and to the practical activities of man is well-known. Of special interest in this respect are solar flares, which throw out fluxes of hot plasma, cosmic rays, x-rays, and intense radio emission. Recently it was established that $\gamma$-rays are also generated at the time of flares (gamma radiation with an energy of about 0.5 Mev was recorded). Obviously, gamma-ray telescopes have now become a permanent part of the instrumentation used for solar research.

Previously, we associated the development of gamma-ray astronomy with the raising aloft of the appropriate equipment (which may be called the gamma-ray telescope) aboard satellites and rockets. Actually, the basic technique of gamma-ray astronomy consists in equipping satellites and rockets with the types of counters used in nuclear physics to record $\gamma$-rays. However this is not the only method. Cosmic gamma radiation of sufficiently high energy can also be recorded in the earth's atmosphere, according to the secondary products it creates ("showers" of electrons, positrons, and softer $\gamma$-rays).

If we take into account the advances made in the technology of satellites and rockets, and also the diversity of methods for recording $\gamma$-rays and the secondary particles they produce, it becomes quite clear that better and better gamma-ray telescopes will now be constructed.

## X-Ray Astronomy. Neutron Stars

As we have already mentioned, x-rays are produced at the time of a solar flare. Solar x-rays have been observed repeatedly and have provided valuable information on the processes developing in the solar atmosphere. The sun is a single phenomenon that can be studied using many methods: optical, radio-astronomical, cosmic-ray variations, etc. Solar x-radiation should thus be discussed within the framework of solar physics. However, this subject will not be treated in detail here, particularly since cosmic x-radiation of nonsolar origin has been discovered and found to be of great importance.

Experiments made with rockets in 1962 and 1963 showed that an isotropic (background) x-radiation exists, which arrives approximately uniformly from all directions. In the wavelength range between 2 and 8 Å (which corresponds to photon energies from 1.5 to 6 kev) an "x-ray telescope" consisting of photon counters records a flux of $\sim 20$ photons/cm$^2$ sec. In addition, discrete sources of x-radiation were discovered in Scorpio and Taurus, and then more than ten other, weaker, sources as well. The fluxes of x-ray photons from the sources in Scorpio and Taurus (in the above wavelength range) are respectively, 20 and 2.5 photons/cm$^2$ sec.

Let us try to determine the nature of the cosmic x-radiation, especially the radiation of the "discrete" sources, which might arbitrarily be called "x-ray stars." No completely definite information has been obtained on this subject as yet. Like $\gamma$-rays, x-rays may be generated when electrons decelerate or collide with ions, or else by electron scattering on optical photons (processes 3 and 4 in Figures 22c and 22d). The only difference is that x-rays are produced by electrons with comparatively low energies (say, less than 30 to 100 Mev), and practically nothing is known about the quantity of such electrons in different parts of the universe. The latter fact is additional evidence of the value of x-ray astronomy, which provides us with data on electrons with the corresponding energies. It should also be kept in mind that x-rays may be produced by relativistic electrons with $E > 10^8$ to $10^9$ ev as well (that is, by the electron component of cosmic rays), as a result of magnetic bremsstrahlung and scattering on radio photons. In the latter case the radio photons have energies $E_\Phi = h\nu = 10^{-3}$ to $10^{-5}$ ev ($\lambda \sim 0.1$ to 10 cm), and there are a comparatively large number of these in the universe (thermal radiation with a temperature of about 3°K; see p. 28).

The observed isotropic x-radiation (x-ray background) may be produced in intergalactic space by Compton scattering of relativistic electrons on optical and radio photons. Although this subject is very interesting* and means exist for finding out more about it (here we are referring mainly to spectral observations and to confirmation of the existence of the isotropic radiation), the problem of "discrete" x-ray sources is a considerably more important one. The primary reason for this is that these sources may be neutron stars, objects which became of interest (although only in theory, of course) as long as about 30 years ago.

The emission of a star is ordinarily maintained by the energy released in nuclear reactions which go on in the stellar interior. As the nuclear fuel "burns up," the star gradually contracts and turns into a dwarf star, consisting of dense ionized gas. However, as the star cools further, calculations show that it may be energetically advantageous for the star to change into a neutron state. This means that protons $p$ combine with electrons $e^-$ to become neutrons $n$, a neutrino $\nu$ being emitted in the process ($p + e^- \rightarrow n + \nu$). In the neutron state a star (called a neutron star) has about the same density as atomic nuclei, which are made up of protons and neutrons (the mean density of nuclear material is about $10^{14}$ g/cm$^3$ = 100,000,000 tons/cm$^3$). Therefore, if a star with the mass of the sun changes into a neutron star, its radius will be only about 10 km, whereas the radius of the visible solar photosphere is 700,000 km (the mean density of the solar material is about equal to the density of water, that is, 1 g/cm$^3$). The amount of light emitted by a star will obviously be proportional to its surface area (to the square of its radius). Consequently, if the sun were to become a neutron star (which is quite improbable in our time), then for the same surface (photosphere) temperature the amount of light emitted by it would be billions of times less. For this reason it was thought for a long time that neutron stars would be unobservable, unless by some miracle they were situated quite nearby. Thus a dramatic situation was created: a hypothesis which was very interesting and of great importance for astrophysics had little hope of ever being verified.

During the last 3 or 4 years, however, it has become clear that this is not the case. Actually, while it is forming, a neutron star becomes heated and for some time (let us say, for hundreds of years, but perhaps for a much shorter time) it may be much hotter than the solar photosphere, the temperature of which is about 6000°K. But the hotter the body, the more it radiates: at thermal equilibrium the energy of electromagnetic radiation is proportional to $T^4$, where $T$ is the surface temperature. Moreover, the

* If the whole of metagalactic space were filled with relativistic electrons having the same concentration as in the Galaxy, the intensity of the x-ray background would be 1000 times higher than that observed. Thus it follows that in the Metagalaxy the concentration of the particles producing the cosmic-ray electron component is less by at least a factor of 1000 than the concentration in the Galaxy.

hotter the body, the more short-wave radiation it emits, in general, so that at the spectral peak the product of wavelength $\lambda$ times temperature $T$ remains the same (displacement law). Accordingly, stars with temperatures of $\sim 10^7$ degrees will emit mostly x-rays.* The intensity of this radiation is so great that present-day "x-ray telescopes" should pick up neutron stars which are thousands of light years away.

Naturally, this subject received the close attention of astronomers and physicists in many countries immediately after the "discrete" x-ray sources in Scorpio and Taurus were discovered. Could not these "x-ray stars" be hot neutron stars? At first glance this hypothesis seems easy to verify. For instance, neutron stars are so small that x-ray sources associated with them should appear to be point sources, for a very high angular resolution. Moveover, the frequency spectrum of thermal emission is quite well-known, so it is possible, in principle, to ascertain whether the source is thermal or not (under the simplest conditions the emission of a neutron star should be thermal). However, it would not do to overlook the shortcomings of the new science of x-ray astronomy. Existing instruments cannot as yet carry out a spectrum analysis, and angular resolution is a veritable "Achilles' heel" of x-ray astronomy. Whereas in optical and radio astronomy angular resolutions of 1" are not uncommon, the resolutions of "x-ray telescopes" were at first several degrees and even now do not usually exceed an angular minute.** Since this is the case, direct determinations of the angular sizes of x-ray sources are not possible, if these objects are considerably less than 1' in size.

Moreover, it is very difficult to identify x-ray sources with visible objects. For example, right after the x-ray source in Taurus was discovered, it seemed quite probable that it was the Crab Nebula. However, this nebula has an angular size of about 5', whereas the source location accuracy in the first experiments did not exceed several degrees (that is, it was tens of times lower than that required to identify the x-ray source with the Crab Nebula). The nature of the x-ray source was even more unclear: it could have been a neutron star located in the Crab Nebula, which had remained after the supernova outburst, or it could have been an extended source associated with this nebula. The moon helped solve this important problem.

On 7 July 1964 the moon occulted the Crab Nebula. At this time a rocket carrying x-ray counters was sent up, and it was found that the signal from the x-ray source begins to weaken just when the Crab Nebula is occulted by the moon. However, as occultation took place, the signal strength (the number of x-ray photons recorded per unit time) decreased gradually rather than sharply. This makes it quite certain that the x-ray source in the nebula is not a neutron star (because of its negligible angular dimensions, such a star would be covered at once and the signal received from it would drop

* The peak of the solar spectrum is reached at $\lambda \cong 5000$ Å. Consequently, for $T = 10^7$ degrees the wavelength $\lambda \approx \frac{5000 \cdot 6000}{10^7} = 3$Å will correspond to the peak.

** The angular resolving power of a gamma-ray or x-ray telescope is limited not by diffraction, which in this case is negligible, but by the very geometry of the instrument, the dimensions of the counters, etc. We know of only one experiment (not counting the method of lunar occultations to be described below) in which a resolution better than 1' was attained. This was carried out in 1966 and it specified the angular size of a very powerful x-ray source (the source in Scorpio) as being less than 20".

sharply to zero; the role of diffraction at the limb of the lunar disk, which is important in the radio range, is completely negligible in this case). The angular size of the x-ray source in the Crab Nebula is about 2'.

In all probability, the x-radiation of the Crab Nebula is connected with magnetic bremsstrahlung, just like the radio emission and most of the visible radiation of this nebula. It follows from formula (8) that, in a field with $H \sim 10^{-3}$ oersted, electrons with energies $E \sim 10^{13}$ ev will be emitted for x-radiation with a frequency $\nu = c/\lambda \sim 10^{18}$ cps ($\lambda \sim 3$ Å). In principle, these electrons may be supplied by the active remainder of the supernova. A conclusive proof of this assumption can be obtained only as a result of a more detailed study, in particular by a determination of the emission spectrum and, especially, by ascertaining the polarization. Therefore, at present it is still possible that the x-radiation from the Crab Nebula is related to magnetic bremsstrahlung (process 3). However, no matter what the final answer may be, the discovery of x-radiation coming from the shell of a supernova has great significance. Recently x-radiation (apparently related to bremsstrahlung) was also found to be coming from the shell of supernova Cassiopeia A.

Even though it turned out that the x-ray source in the Crab Nebula was not a neutron star, it may still be possible to observe neutron stars according to their x-radiation. However, it is now believed that neutron stars may enter into a special ("superfluid") state, which leads to a more rapid cooling of the star. There are also other reasons for believing that the "hot phase" of a neutron star only lasts for a short time. Therefore, it may be that a distant neutron star can be observed in the x-ray range only for a few years, months, or even days after its formation. Conditions may also exist under which a neutron star stays hot for a long time.* In addition, the frequency of occurrence of neutron stars in the Galaxy is unknown. Thus it is not completely certain that it will be possible to observe any neutron stars in the near future. But is scientific research carried out only when the result is already known or when there is no doubt that the research will be successful? As we know, this is far from being the case, and thus searches for neutron stars will definitely be one of the most interesting tasks of x-ray astronomy.

The brightest x-ray source lies in the constellation Scorpio (source Scorpio XR-1 or, according to another system, Scorpio X-1). This source was the first one discovered (1962 -1963), but the nature of Scorpio XR-1 was actually clarified only in 1966. A small "blue" star was found to be located at the site of this source, evidently a former nova. Most, and possibly all, novae are close binaries, that is, they are actually two stars lying close to one another and revolving around their common center of gravity (at the time of a nova outburst one of these stars throws out a gaseous shell or several shells). If the mass of one of the stars is much greater than that of the other, then this "heavier" component of the binary will attract gas from the shell of the other (lighter) star. As a result, there is a flow of gas to the heavy star. If the radius of the latter is small (especially if it is a neutron star), then the gas incident on its surface will be traveling very fast and will heat the surface layer of the star considerably. In short, for such a close binary system, under the proper conditions there will be an

* This will be the case if a neutron star is located in a fairly dense cloud of gas. Then, the incident gas flow becoming attached to the star as a result of its gravitational attraction (the so-called accretion) will heat it up.

intensive gas flow and a concomitant heating both of this gas and of the surface of one of the stars. It is quite probable that these factors are responsible for the high x-ray luminosity of source Scorpio XR-1 and objects similar to it. Therefore, in this case the x-radiation is associated with bremsstrahlung. Such a conclusion is in full agreement with spectral data for Scorpio XR-1, since the latter data are identical to the data for bremsstrahlung of a hot gas (temperature $T \approx 5 \cdot 10^7$ degrees). Consequently, there are two kinds of x-ray sources in the Galaxy: extended sources (shells of supernovae) and starlike sources (probably, stars which are former novae and in general are close binaries). It is also quite possible that there are neutron stars which are bright in the x-ray range (that is, which are fairly hot).

In all probability, there are similar sources in other galaxies. However, it is even more interesting to consider the possibility of an x-ray galaxy, that is, a galaxy which is especially bright in the x-ray range. In this case we would be dealing with x-radiation from enormous clouds of hot gas or else with magnetic x-ray bremsstrahlung from regions of galactic size. In 1966 such an intense x-radiation was thought to have been detected in the emission of radio galaxies Cygnus A and Virgo A. However, in the case of Cygnus A this result was contradicted by other observations, while the existence of x-radiation from Virgo A remains an open question (the measurements have not been repeated). Studies of the x-radiation of extragalactic objects (galaxies, radio galaxies, and quasars) constitute one of the most important, and one of the most disturbing, tasks of x-ray astronomy, and actually of astronomy as a whole. Whatever the solution of this problem will be, we have seen that the initial steps of gamma-ray and x-ray astronomy have already led to some significant results and discoveries. Undoubtedly, a great deal of new information concerning the structure of the universe will be obtained using these methods. In this respect, it is especially significant that the cosmic gamma and x-radiations are intimately associated with ordinary cosmic rays. Thus we have one more means of studying cosmic rays in the universe at tremendous distances from earth.

*Chapter 4*

## *THE ORIGIN OF COSMIC RAYS*

According to observational data, in our Galaxy cosmic rays are definitely produced by the sun and during supernova outbursts. Therefore, it is natural to assume that other stars can also emit cosmic rays. But what role do the different sources play, and how are the cosmic rays which reach the earth produced? And how are charged particles accelerated to cosmic-ray energies as a result of supernova outbursts, as well as on the sun and other stars? Such questions concerning the sources and acceleration mechanisms of cosmic rays can also be asked, of course, in relation to other galaxies, and in particular in relation to radio galaxies and quasars.

A theory of the origin of cosmic rays should provide answers to all such questions. Let us begin with our own Galaxy and the origin of the cosmic rays observed near the earth (to simplify the discussion, it will not be stipulated in the following that just our Galaxy is referred to).

### The Energy Balance. Cosmic-Ray Sources

One of the most important requirements which a cosmic-ray energy source must satisfy is based on energy considerations. The protons and nuclei which constitute the main part of the cosmic rays are continually losing energy as a result of collisions with nuclei of the interstellar medium. The effective cross sections for such collisions are known, albeit not very accurately. These are listed in Table 2 for collisions of the nuclei of different groups, moving in hydrogen. The interstellar gas is a mixture whose composition was given back in Table 1 (Chapter 1). The discrepancies introduced when the medium is assumed to be hydrogen are not great, and they are certainly not significant, in view of the fact that the density of the interstellar medium is not accurately known. Table 2 also shows some tentative values of the mean free path $l$ and the time of free particle flight, for a medium with an average hydrogen concentration $n = 0.01$ cm$^{-3}$.*

As a result of the splitting up of heavy nuclei, lighter nuclei and protons are produced, but the mean energy per nucleon varies comparatively little.

* The mean free path $l$ is defined as $1/\sigma n$, where $\sigma$ is the effective cross section and $n$ is the mean concentration of nuclei of the medium (in the given case hydrogen nuclei (protons)). The quantities $l$, $\sigma$ and $n$ are measured correspondingly, for example in cm, cm$^2$, and cm$^{-3}$. In g/cm$^2$ the quantity $l$ is equal to $\rho/\sigma n$, where $\rho = Mn$ is the mean density of the medium and $M$ is the mass of the nuclei which make up the medium. For hydrogen $M = M_p = 1.67 \cdot 10^{-24}$ g. The lifetime $T_n$ for collisions with a mean free path $l = 1/\sigma n$ is $T_n = l/v \approx l/c$, since the cosmic-ray velocity $v$ is essentially equal to the velocity of light $c$.

Consequently, the losses in cosmic-ray energy are determined by the nuclear lifetime of the protons, $T_0 \approx 5 \cdot 10^9$ years $\approx 1.5 \cdot 10^{17}$ seconds. However, this will be the case only in the absence of other losses, aside from the losses due to nuclear collisions. In practice, for protons and nuclei with cosmic-ray energies, only the escape of cosmic rays from the Galaxy (from the halo) into extragalactic space need be considered in addition to nuclear collisions. Unfortunately, the time $T_e$ characterizing such particle escapes is not accurately known. It may be assumed to be $\sim 3 \cdot 10^8$ years. Therefore, taking into account the approximate nature of the evaluations to be carried out below, the effective (from the point of view of energy losses) lifetimes of cosmic rays in the Galaxy will be of the order of $T_e \sim 3 \cdot 10^8$ years $\approx 10^{16}$ seconds. For heavy nuclei the lifetime of the nucleus will be $T_n \lesssim 2 \cdot 10^8$ years. Consequently, the lifetimes of cosmic rays, and especially of heavy nuclei, are considerably less than the age of the Galaxy, $T_g \sim 10^{10}$ years $\approx 3 \cdot 10^{17}$ seconds. Thus it is clear that the cosmic rays being observed today, most of which were produced in the form of nuclei, are "young" in comparison with the age of the Galaxy.

TABLE 2. Effective cross sections, mean free paths, and lifetimes of cosmic rays

| Nucleus group | Effective cross section $\sigma$, in units of $10^{-26}$ cm$^2$ | Mean free path $l$, g/cm$^2$ | Lifetime $T_n = l/c$, $10^8$ years |
|---|---|---|---|
| $p$ | 2.3 | 74 | 50 |
| $\alpha$ | 9 | 18 | 10 |
| $L$ | 23 | 7.3 | 5 |
| $M$ | 29 | 5.8 | 4 |
| $H$ | 48 | 3.5 | 2 |
| $VH$ (Fe) | 70 | 2.4 | 1.5 |

The galactic halo, which is full of cosmic rays, has a volume of about $V \sim \frac{4\pi}{3} R^3 \sim 10^{68}$ cm$^3$, since the mean radius of the halo is $R \approx 3 \cdot 10^4$ light years $\approx 3 \cdot 10^{22}$ cm. Assuming an average cosmic-ray energy density in the halo of $w_{c.r.} \sim 0.3$ ev/cm$^3$ $\sim 5 \cdot 10^{-13}$ erg/cm$^3$, we find the following value for the total energy of the cosmic rays in the Galaxy: $W_{c.r.} \sim w_{c.r.} V \sim 10^{56}$ ergs. If the supply of new cosmic rays were to stop, the total cosmic-ray energy of the system would change significantly during the lifetime $T_e \sim 10^{16}$ seconds. Obviously this means that, to maintain an equilibrium state in which the cosmic-ray energy in the Galaxy does not change, the sources of these rays must have a power

$$U \sim \frac{W_{c.r.}}{T_e} \sim 10^{40} - 10^{41} \frac{\text{erg}}{\text{sec}}, \tag{13}$$

where the larger of these values is indicated in order to have the required error margin for the calculations.

It is not so easy to provide a source power of the order of $10^{40}$ erg/sec. The average power of solar cosmic rays, for example, apparently does not exceed $10^{23}$ to $10^{24}$ erg/sec. Therefore, even if all the $10^{11}$ or $10^{12}$ stars of the Galaxy emitted cosmic rays with powers comparable to that of the solar cosmic rays, the total would be only $10^{-4}$ to $10^{-6}$ of that required to maintain the balance. This example is very significant. To say that cosmic rays may be generated on stars by no means explains the origin of all the cosmic rays observed at the earth. In order to substantiate the purely "stellar" origin of cosmic rays, it must be assumed that very many stars are incomparably better cosmic-ray emitters than the sun. In this respect the hypothesis of a "stellar" origin for most cosmic rays runs into serious difficulties. Aside from the energy considerations, it should be mentioned that solar cosmic rays have an energy spectrum and chemical composition which are quite different from those of the cosmic rays coming to us from interstellar space. (In order to avoid misunderstandings, let us note that here a "stellar" origin of cosmic rays refers only to the acceleration of particles at nonexploding stars.) It is our opinion that the hypothesis of a stellar origin for most cosmic rays cannot be well substantiated at present, particularly since the origin of cosmic rays can be explained in terms of supernova outbursts.

The following arguments speak in favor of such an explanation. The presence of a large number of electrons with cosmic-ray energies in the shells of supernovae has been definitely established. The energies of these electrons in Cassiopeia A and in the Crab Nebula amount to $10^{47}$ to $10^{48}$ ergs. The energies of all the cosmic rays in some of these sources are probably a hundred times higher.* Consequently, in each supernova outburst (or at any rate in some of them), cosmic rays having energies up to $10^{49}$ to $10^{50}$ ergs are produced, and these energies may reach $10^{51}$ ergs (see below). Some 50,000 to 150,000 years after the explosion of a star, the shell has essentially become dissipated in the interstellar medium, and the cosmic rays disperse in free space. This takes place mainly in the regions where most of the stars are, such as in the spiral arms and in the central regions of the Galaxy. However, the cosmic rays do not remain for long in the place where they were created: moving along the force lines of the field, they fill the entire galactic halo.

Values of $10^{49}$ or $10^{50}$ ergs for the cosmic-ray energies in the shells may be somewhat exaggerated (for example, as noted, the energy of all the cosmic rays in the Crab Nebula may be of the order of the energy of the electron component alone). On the other hand, some of the cosmic rays may leave the shell during an earlier stage of its development, that is, during the actual supernova explosion. The total energy liberation during a supernova outburst attains $10^{50}$ to $10^{51}$ ergs, and it may even be $10^{52}$ ergs. Therefore, the average power of the cosmic rays entering interstellar space from supernovae can be evaluated. It will be equal to the outburst energy $W_{out} \sim \sim 10^{49}$ to $10^{51}$ ergs divided by the average time $T_{out}$ between outbursts, which is 50 to 100 years. Thus the power of the cosmic rays generated by supernovae is

$$U_{sn} \sim \frac{W_{out}}{T_{out}} \sim 3 \cdot 10^{39} - 3 \cdot 10^{41} \frac{\text{erg}}{\text{sec}}. \qquad (14)$$

* This value was obtained from a comparison with data on the cosmic rays in the Galaxy, from considerations of the approximate equality of the cosmic-ray energy and the energy of the magnetic field, and also from an analysis of the dynamics of shell dispersion. However, it should be noted that in the case of the Crab Nebula and similar supernovae (supernovae of type I) the energy of all the cosmic rays probably is not an order of magnitude higher than the energy of the electron component.

If we compare this value with the required power (13), it is easy to see that supernovae can actually ensure that the balance be maintained. It should be also mentioned that there are no existing observational data which provide definite evidence of the existence in the Galaxy of other cosmic-ray sources having a power comparable to that of a supernova. However, if we make use of more or less plausible estimates rather than observational data, then novae may be significant as well. The energy released during a nova outburst is thousands of times less than that for a supernova, but at the same time novae occur thousands of times more frequently. The fact that no radio emission has as yet been detected from novae is not a decisive factor, since very weak radio sources are difficult to detect and identify.

Possible explosions of galactic nuclei are hypothetical cosmic-ray sources which are even more important than novae. We have noted that, at present, the nucleus of our Galaxy does not seem to be an especially active region. However, a certain activity and some nonthermal radiation is observed in the nucleus. Moreover, radio galaxies and several other galaxies (and possibly quasars as well) are proof that galactic nuclei can explode. In all probability, such an explosion (for instance, the explosion in the photograph of galaxy M 82 shown in Figure 20) is not an explosion of a large number of supernovae but rather the explosion of a single gigantic supernova (having a mass of as much as $10^8 M_\odot$). It may be that such explosions have sometimes also taken place in the nucleus of the Galaxy, which is similar to a small quasar; the last explosion, of course, would have occurred from $3 \cdot 10^7$ to $5 \cdot 10^7$ years ago or even earlier. The explosions in the nucleus of the Galaxy were probably not very powerful (otherwise the Galaxy would now most likely be a radio galaxy, which is not the case). "Small explosions" which liberate an energy $W_{\mathrm{exp}} \sim 10^{55}$ to $10^{56}$ ergs in cosmic rays will, if they occur every $3 \cdot 10^7$ to $10^8$ years on the average, correspond to an average injection power $U_{\mathrm{exp}} \sim 10^{40}$ to $10^{41}$ erg/sec. In this case the explosions would play approximately the same role as supernovae, but the reserve of cosmic-ray energy $W_{\mathrm{c.r.}}$ in the Galaxy would undergo marked oscillations. Definite means exist for checking this possibility, but as yet the problem has not been solved satisfactorily. Rather, preliminary data indicate that there have been no marked variations of $W_{\mathrm{c.r.}}$ during the last $10^8$ to $10^9$ years and in general they conflict with the assumption that a sizable part of the cosmic rays observed at the earth are the product of one or two powerful explosions. However, there are no real objections to small explosions in the nucleus of the Galaxy, and in fact there is even certain evidence which indicates that such explosions do occur.

Thus, at present it is more probable that the majority of the cosmic rays in the Galaxy are produced during supernova outbursts, and possibly during nova outbursts as well, and in particular during explosions in the galactic nucleus (provided such explosions occurred in our Galaxy during the last $10^8$ to $10^9$ years). The cosmic rays are generated in sources which are rich in heavy nuclei, but as they migrate through interstellar space some of the nuclei decay and light nuclei ($He^3$, Li, Be, B, etc.) which are rarely found in nature are produced. As a consequence, the chemical and isotopic composition of the cosmic rays varies significantly en route.

The electron component of the cosmic rays, which is responsible for the nonthermal cosmic radio emission, is only to a small extent caused by secondary processes (formation of $\pi^\pm$ mesons with subsequent $\pi^\pm \to \mu^\pm \to e^\pm$

decay). Therefore, the cosmic-ray sources must also supply relativistic electrons. The corresponding power of the sources of the electron component is

$$U_e \sim 3 \cdot 10^{38} - 3 \cdot 10^{39} \frac{\text{erg}}{\text{sec}}, \tag{15}$$

which is one or two orders of magnitude less than the power of the sources of all the cosmic rays (cf. (13)). Accordingly, the acceleration of the electrons does not constitute a special problem, from the point of view of energy. At the same time, the necessity to accelerate both heavy nuclei and electrons undoubtedly imposes additional requirements upon the sources.

As will be seen below, the acceleration mechanism of the cosmic rays at the sources is still not definitely known. In general, the theory of the sources and the overall understanding of the processes taking place in them lag considerably behind our understanding of the "external problem" (the nature of the motion and transformations of cosmic rays outside the sources, general ideas on the behavior and role of cosmic rays in galaxies and supernova shells, etc.). It is especially important to note that the problem of sources (the "internal" problem") differs significantly from the "external problem," as a result of the use of data from observations and measurements.* For example, we make use of data on the energy of the cosmic-ray electron component in supernova shells, which follow directly from measurements of the radio-emission fluxes of these shells.**

Therefore, it may be assumed that the above description of the origin of the cosmic rays in the Galaxy corresponds to reality, as far as its main points are concerned. However, some astrophysicists disagree with this explanation. Some maintain that the cosmic rays observed at the earth are primarily metagalactic in origin, that is, that they come to the earth from metagalactic space. We consider this to be very improbable. However, since it is impossible to rule out this possibility, and especially since cosmic rays outside the Galaxy are a subject of great interest, let us consider them now.

## Cosmic Rays Outside the Galaxy

The cosmic rays outside the Galaxy are concentrated, first of all, in "normal" galaxies, radio galaxies, and quasars. Secondly, cosmic rays are present between the galaxies as well, in intergalactic (or, as it is often called, metagalactic) space. In the latter case let us refer to them as metagalactic cosmic rays.

* Here we can draw an analogy with "interior" and "external" ballistics, both from the point of view of terminology and with respect to the essence of the problem. Whereas external ballistics is the study of projectile motion during flight, interior ballistics studies the explosion process and the motion of a shell in the gun barrel.

** Strictly speaking, to determine the energy of all the relativistic electrons in the source, the strength of the magnetic field there should also be known. However, the energy of the electrons will be a minimum if it is of the same order as the energy of the field. It is usually assumed that this is the case. At any rate, such an assumption does not lead to an exaggeration of the supply of relativistic electrons in the source, which is especially important in our case.

Galaxies and quasars differ from one another by the shape of the radio-emitting regions and by the radio-emission power. To some extent, these differences are related to the fact that the systems are in different stages of evolution (for example, different times may have passed since the explosion of a galactic nucleus). However, this is certainly not the only factor, since great differences exist between the galaxies themselves: some are gigantic systems with masses up to $M \sim 10^{12}\ M_{\odot} \sim 10^{45}$ g (an order of magnitude larger than the mass of our Galaxy), and some are dwarf galaxies with masses $M \sim (10^8$ to $10^9)\ M_{\odot}$. In most galaxies, as in our stellar system, there are occasional supernova flareups. Therefore, this source of cosmic rays must be considered here as well. It is highly improbable, however, that the tremendous quantity of cosmic rays present in radio galaxies are produced by this means. They were probably accelerated during the explosion of the galactic nucleus. Some portion of the cosmic rays generated by radio galaxies, other galaxies, and quasars enter metagalactic space, where they move through the intergalactic magnetic fields (the configuration and strength of the metagalactic field are unknown, so that the nature of the motion of the metagalactic cosmic rays can only be assumed).

Obviously, metagalactic cosmic rays not only arrive from galaxies,* they also penetrate into them (in particular, they may enter our Galaxy). What, then, is the role of these metagalactic cosmic rays in observations made at the earth? This will be the basic question of interest to us.

If we consider particles with ultrahigh energies ($E \gtrsim 10^{15}$ ev), which are extremely few, then there is no special problem. It is quite possible, for example, that a considerable portion of these particles were produced in intense radio galaxies. In such a case the energies attained will be higher than those for the acceleration of cosmic rays in the Galaxy. In addition, ultrahigh-energy particles are difficult to keep within the Galaxy, so that there is even more reason to assume that these particles are collective, that they belong to the Metagalaxy and only "look in on" the Galaxy for a time. Another thing is that the quantitative aspect of the question is still not clear. Considerable study will be necessary before cosmic rays in the high and ultrahigh energy ranges can be divided into their metagalactic and galactic components (here the galactic component refers to the portion of the cosmic rays produced in the Galaxy).

The cosmic-ray spectrum drops rapidly with the energy (see Figure 4, which is plotted on a logarithmic scale). Consequently, the cosmic-ray energy density $w_{\text{c.r.}}$ will be completely determined by the particles with comparatively low energies $E \sim 10^9$ to $10^{10}$ ev. It is just with regard to the origin of this basic part of the cosmic rays, which determines their energy role and their pressure, that different opinions exist.

It is quite evident that metagalactic cosmic rays would be dominant in the Galaxy only if their concentration were high enough, practically the same as the observed cosmic-ray concentrations at the earth. However, if we consider all of metagalactic space, we see that such an assumption is

* This does not mean that all the metagalactic cosmic rays must be produced in galaxies. On the contrary, some portion of these cosmic rays may have been created during the formation of galaxies, or even somewhat earlier (according to present-day theory, the universe is not stationary; about 9 or 10 billion years ago the state of the universe was considerably different from that observed today, and then the galaxies had not yet formed).

highly unlikely. First, all the galaxies together (including radio galaxies) are not capable of "supplying" so many cosmic rays that the whole Metagalaxy would be filled with them to the required density. This has been shown by various estimates. Therefore, the only alternative is to assume, purely hypothetically, that the cosmic rays were accelerated very strongly duing the pregalactic stage of evolution of the Metagalaxy. Secondly, various data (especially data on the fluxes of cosmic $\gamma$-rays and x-rays, see Chapter 3) indicate that there are considerably fewer cosmic rays (or, more precisely, particles of the electron component) in metagalactic space than at the earth. Thus, the only way to "save" the metagalactic theory of the origin of the cosmic rays near the earth is to assume that metagalactic cosmic rays are not numerous everywhere in the Metagalaxy, but only in the vicinity of our Galaxy and in its surroundings. This would be logically possible, for instance, if there were a powerful radio galaxy near our Galaxy. Then a steady state would not be possible, and the cosmic-ray flux would vary greatly during a time comparable to the duration of the active phase of a radio galaxy ($10^6$ to $10^8$ years). So far, however, there has been no indication that this is the case, and a marked unsteady state has not been observed in the neighbourhood of our Galaxy. For these same reasons, we were led to assume that most of the cosmic rays in the Galaxy were produced there.

However, the problem of the metagalactic cosmic rays and their role in the Galaxy is too fundamental to assume that the foregoing considerations are conclusive. Thus we must not adopt a hasty solution; rather, we must seek every new means of checking and analyzing the different possibilities. One means which has recently been used to carry out such an analysis consists in taking into account specific plasma phenomena which accompany the motion of cosmic rays through interstellar and intergalactic space (the interstellar gas, and especially the intergalactic gas, become ionized and produce a plasma). As they move through the plasma, particle beams generate waves of different types, and the interactions between these waves and the cosmic rays must be allowed for.

Thus, to sum up, metagalactic cosmic rays are of exceptional interest, even if their concentrations are comparatively small, as we have assumed. In particular, they help us interpret the data of gamma-ray and x-ray astronomy. Moreover, and this is very important in our case, it is impossible to understand the behavior and the properties of the intergalactic medium without taking into account cosmic-ray effects. Finally, it may be that the intergalactic gas, the concentration of which is still unknown, is the most massive substance in the universe (the upper limit for the mass of this gas is about 30 times greater than the mass of all the galaxies).

## The Mechanism of Cosmic-Ray Acceleration

One very important feature of the above theory of the origin of cosmic rays is the inclusion of radio-astronomical data indicating that cosmic rays are present in supernova shells, in the Galaxy, in "normal" galaxies, in radio galaxies, and in quasars. Thus, as we have already noted, to some extent it is possible to discuss separately the cosmic-ray sources themselves and the mechanism of cosmic-ray acceleration in these sources. In other words, many conclusions are fortunately not dependent on how the particles are accelerated to relativistic energies. However, this does not mean, of course, that the latter problem does not deserve full attention too.

The mechanisms of particle acceleration in the sun, in the shells of supernovae, and in other parts of the universe have by no means already been explained satisfactorily. Nevertheless, some possible explanations have been suggested. With one exception (acceleration in shock waves with increasing amplitude) all known existing mechanisms for the acceleration of charged particles in space are in some way connected with the action of the inductive electric field which appears when a magnetic field increases.

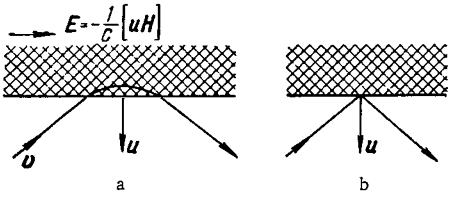


FIGURE 23. "Collision" between cosmic particle and moving inhomogeneity of magnetic field. Magnetic field in shaded region (gas cloud) moving with velocity $u$ normal to plane of the diagram (outside this region there is no field):

a) actual collision; b) "equivalent" collision.

The simplest electromagnetic mechanism is caused by the increase of a uniform (or quasiuniform) magnetic field with time. Except at stars, however, sizeable and prolonged increases of the magnetic field are not usually encountered under cosmic conditions.* Accordingly, the acceleration associated with "collisions" between a particle and moving inhomogeneities in the magnetic field becomes more important. For such collisions (Figure 23) acceleration of the particle is caused, in the final analysis, by the inductive electric field arising when gaseous masses with "frozen-in" magnetic fields are in motion.** However, it is not necessary to consider the actual collision process, since only the result is important. Therefore, it will be sufficient to use the laws of conservation of energy and momentum. (Strictly speaking, this is just the way we study any other collision, for instance, when a steel ball strikes a metal or stone plate; in this case, at the time of the actual collision the ball penetrates into the plate somewhat, just as in Figure 23a.) The actual collision (Figure 23a) will be replaced by an "equivalent" (from the point of view of the final result) reflection of the particle from an impenetrable "wall," moving with the same velocity $u$ (Figure 23b).

It follows from the conservation laws that at the time of collision the total energy $E$ of the particle varies by an amount $\Delta E$:

$$\Delta E = -\frac{2E}{c^2}(uv), \qquad (16)$$

* When spots appear on the sun and stars, and also for so-called magnetic stars, betatron acceleration may become very significant. The same may be the case for the hypothetical debris of supernovae, that is, for the stars which remain after the explosion and casting off of the shell. Here, however, we are mostly interested in other conditions (supernova shells, etc.).

** For the motion of a good conductor, such as ionized interstellar gas, there will be practically no electric field in a frame of reference associated with the medium. If a magnetic field of intensity $H$ exists, and the medium moves with a velocity $u$ relative to the frame of reference, then in this system there will be an electric field with an intensity $E = -\frac{1}{c}[uH]$, assuming that $u \ll c$.

where $v$ is the particle velocity prior to impact, and $u \ll c$ (in the calculation we also made use of the fact that the energy of the particle is negligible in comparison with the kinetic energy of the wall). From (16) it is evident that, for example for a head-on collision between the particle and a wall moving toward it, the particle energy will increase by an amount of $\Delta E = \frac{2E}{c^2} uv$ (for a nonrelativistic particle the total energy will be $E \approx Mc^2$, so that $\Delta E \approx 2Muv$).

Now let us assume that we have two walls moving toward one another. The front of a magnetohydrodynamic shock wave or a gaseous mass carrying a magnetic field may be equivalent to such walls under cosmic conditions. A charged particle which enters the space between the walls (Figure 24) will be accelerated until it leaves the system or else until the walls approach to a distance comparable to the radius of curvature of the particle trajectory in the magnetic field of the walls. The total increment in particle energy will obviously be equal to the energy variation for one collision times the number of collisions.

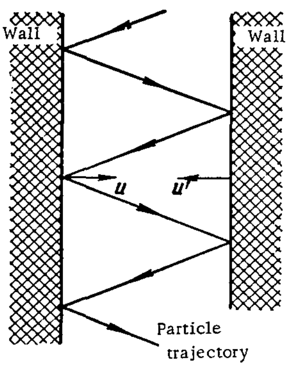


FIGURE 24. Particle acceleration between walls moving opposite to one another (wall velocities $u$ and $u'$).

Such will be the mechanism for the systematic acceleration of particles in a moving medium with magnetic fields. This mechanism is relatively effective (acceleration proportional to $u/c$; for instance, for $u = 3000$ km/sec the energy of a relativistic particle will double as a result of $n = c/2u = 50$ collisions). However, this systematic acceleration cannot continue for long; after some time the walls will converge. Therefore, under cosmic conditions so-called statistical accelerations are generally of greater importance. In this case the particle undergoes both head-on collisions and overtaking collisions in which the particle energy decreases. However, head-on collisions are somewhat more probable, so that on the average the particle energy increases, but this increase will be proportional to $u^2/c^2$ instead of $u/c$. Naturally, then the energy increases more gradually (we recall that $u/c \ll 1$), but at the same time the acceleration process may continue for a very long time (the acceleration period is determined by the time when the particle leaves the region with the moving gaseous masses, by the duration of the violent motions in a stellar envelope, etc.).

In the case of supernova outbursts, with their subsequent shell expansion, the details of the acceleration process are still not clear. This is understandable, if we take into account that very little is known about the course of a stellar explosion and the formation of a shell. The only thing that can be said definitely is that the shells contain all the "ingredients" necessary for acceleration, at any rate during the first stages after explosion; these ingredients are: moving gaseous masses, magnetic fields, and sufficiently rapid particles.

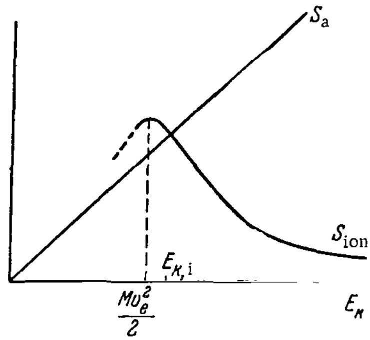


FIGURE 25. Ionization-loss rate $S_{ion}$ and rate energy growth through acceleration $S_a$, as functions of kinetic energy of particle $E_K$.

The last condition is related to the necessity for an injection energy. Even when acceleration mechanisms are present, the particle may not pick up energy, due to the preponderance of deceleration mechanisms. One of the most important of the latter is ionization losses: when a charged particle moves through a medium, it loses energy as it ionizes the medium. Such losses will also exist in a completely ionized medium: in this case the energy of the particle is used up, roughly speaking, by the "repulsion" of the particles of the medium. The term "ionization losses" thus should not be taken literally in this case.

The ionization-loss rate (losses per unit time) $S_{ion}$ varies with the kinetic energy of the particle $E_K$, as shown in Figure 25. The losses reach a maximum when the particle velocity $v$ is approximately equal to the velocity $v_e$ of the electrons of the medium in which the particle moves (the kinetic energy of the particle $E_{K,max}$ at maximum loss is thus approximately $Mv_e^2/2$).

The rate $S_a$ of the energy increase caused by the action of the acceleration mechanisms is usually a monotonically increasing function of $E_K$. In the simplest case this rate is just proportional to $E_K$, as shown in Figure 25. The curves for $S_{ion}(E_K)$ and $S_a(E_K)$ are seen to intersect at a point, which corresponds to a certain energy $E_{K,i}$. This value is known as the injection energy; acceleration takes place only if the particle has previously obtained, in some way or other, an energy $E_K > E_{K,i}$. However, there is an important exception to this rule: a particle may accelerate without injection (preacceleration) if the $S_a$ curve lies above the maximum of the $S_{ion}$ curve (see curves 1 and 3 in Figure 26). For a particle (ion) with a given charge, the loss curves $S_{ion}(E_K)$ become shifted to the right for higher values of the particle mass $M$. This is quite understandable, since the losses are a maximum for $v \approx v_e$, that is, for $E_{K,max} = Mv_e^2/2$.

From this we can draw a conclusion which may be of fundamental significance with respect to the acceleration of cosmic rays. Conditions are possible (see Figure 26) under which injection is necessary for lighter particles but not necessary for heavy particles. Under these conditions there will be a predominant acceleration of heavy particles, so that the resulting cosmic rays will consist mainly of heavy nuclei. Moveover, it may be assumed that the conditions favorable for the acceleration of just heavy nuclei are the rule, rather than the exception. In this way it may be possible to explain the fact that there are an especially large number of heavy nuclei in cosmic rays.

It should be stressed once more that the mechanism of cosmic-ray acceleration during explosions of supernovae and of galactic nuclei can by no means be considered to have been explained as yet; in the foregoing we have only attempted to show how, in principle, this acceleration may take place.

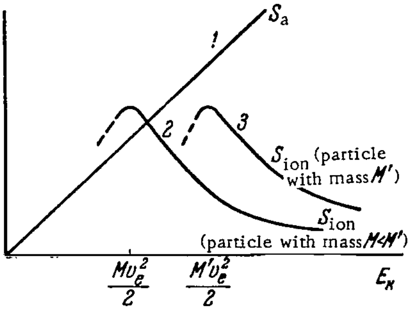


FIGURE 26. A sufficiently heavy particle may be accelerated without injection (curves 1 and 3). For lighter particles injection (preacceleration) is required (curves 1 and 2).

However, such a situation should not be surprising, if we take into account that an explosion of a supernova or galactic nucleus has never been observed in detail, and that the nature of such explosions is not known. On the other hand, even in the case of the sun, which is close to us, the mechanism of the cosmic-ray acceleration has still not been explained satisfactorily. It is known that this acceleration takes place primarily as a result of solar flares. In the vicinity of a flare quite intense magnetic fields are known to exist, the configurations of which vary during the flare. It appears that during a flare the energy of the magnetic field is converted directly into kinetic energy of fast particles. The conditions of this conversion (in principle, it may be some form of electromagnetic acceleration) are still not known and are being studied at present. It may be that something similar, but on a much larger scale, of course, takes place when a supernova or galactic nucleus explodes.

*CONCLUSION*

Studies of the cosmic rays throughout the universe, rather than just near the earth, were actually begun less than 15 years ago. In the course of these studies it was found that cosmic rays are present everywhere (except, of course, in the denser layers of the stars and planets) and that they are especially abundant in regions which are in a state of intensive evolution, explosion, etc. What is more, in many cases cosmic rays are significant dynamically and energetically. For instance, during the dispersion of radio-emitting "clouds" in radio galaxies, in the halos of normal galaxies, and in the shells of supernovae, the cosmic-ray pressure is, at any rate, no less important a factor than the gravitational forces, which were previously thought to be predominant in the universe. As recently as several years ago, the universe was still in general thought to consist of stars, gas, and solid bodies (planets, cosmic dust, etc.), together with electromagnetic radiation. Now, however, cosmic rays must definitely be included as basic elements of the universe.

Much has already been accomplished in the astrophysics of cosmic rays, but there are still many problems which await solution. This also applies to studies of the primary cosmic rays near the earth, and to studies of cosmic rays throughout the universe using the techniques of radio, optical, gamma-ray, and x-ray astronomy.

There are several important factors which may be said to characterize the present developmental stage of astronomy: complexity of approach, the use of a variety of research methods, a remarkable refinement of the apparatus, launchings of more and more sophisticated satellites, and the development of theoretical astrophysics. All the above factors make it quite clear that, during the next few years, a great many new things will be learned about the cosmic rays near the earth and throughout the universe.

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